CO_2 ReUse NRW

Evaluating gas sources, demand and utilization for CO_2 and H_2 within the North Rhine-Westphalia area with respect to gas qualities

supported by Climate-KIC Deutschland, Berlin

Final Report

September 2015

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Climate-KIC is supported by the EIT, a body of the European Union

Wuppertal, September 2015

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Introduction

To achieve the national and global climate protection objectives, a full decarbonisation of all sectors in the energy system will be necessary in the long term until the turn of the century. While the transformation towards renewable energy sources is already well advanced in the electricity sector, approaches of extensive decarbonisation exist only isolated. This is despite the fact that the energy efficiency potential of the energy intensive industry has already been largely exhausted for economic considerations and compared to other sectors disproportionate savings have been achieved.

Today the CO_2 utilisation is discussed as one of the future low-carbon technologies. CO_2 is separated from the flue gas stream of power plants and is prepared for further processing as raw material. Fossil resources will not only be used as fuel in the industrial sector but also as feedstock for production of different products (e.g. urea, fertilizer, polymer materials). CO_2 containing gas streams from industrial processes exhibit a higher concentration of CO_2 than, for instance, flue gases from power plants which contain for example a high percentage of nitrogen. On the one hand it is therefore obvious to use industrial CO_2 sources as raw material for the chemical industry and for the synthesis of fuel on the output side. On the other hand, fossil resources can be replaced by substitutes of reused CO_2 on the input side. If set up in the right way, this step into a CO_2-based circular flow economy could make a contribution to the decarbonisation of the industrial sector and according to the adjusted potential, even rudimentarily to the energy sector.

In this study the potential CO_2 sources, the potential demand and the range of applications of CO_2 are analysed by the case study of North Rhine-Westphalia (NRW). Since activation energy is needed for the reuse of CO_2 and the utilisation usually depends on the use of hydrogen as a source of energy, it is necessary to view also regional sources and usage possibilities of hydrogen. NRW with its high density of (energy-intensive) industry is well suited for this analysis.

At first, **chapter one** analyses the CO_2 sources which are expected to be available in the middle-term (time frame until 2030) under the conditions of a stringent climate protection policy. Therefore, industrial point sources of the chemical industry, the iron and steel industry, the cement and lime industry, coking plants and refineries are considered as well as CO_2 sources of large combined heat and power plants (hard coal and natural gas), waste incineration plants and biomethane plants. The potential CO_2 streams are scrutinised quantitative (CO_2 amount), qualitative (CO_2 concentration) and on their regional distribution. Analogue industrial hydrogen sources are regarded concerning their available amount and their regional distribution.

Chapter two considers current and potential utilisation options of CO_2 and $H_{2.}$ Thereby, the utilisation as a chemical raw material is discussed as well as the synthesis to gaseous (Power-to-Gas) and liquid fuels (Power-to-Fuels). Furthermore, an overview about current projects and research activities is shown.

In **Chapter three** the identified potentials of CO_2 and H_2 sources of chapter one are linked to the potential utilisation options (sinks) of chapter two. The concrete spectrum of theoretical potentials of reusing CO_2 in NRW is estimated regarding a discussion about the preconditions and limits of appropriate paths of exploitation of $CO_{2.}$ Therefore, location issues are of crucial importance as they influence the decision of the media (flue gas, separated CO_2, H_2, electricity, methane, raw materials, …) which has to be carried.

To contribute to a sustainable development, CO_2 value chains have to be not only technically stable, but also ecologically, economically and socially. **Chapter four** develops the methodological background for a systematic multi-criteria-analysis (MCA) of potential value chains of CO_2 reusing[1]. Therefore, a general overview of different approaches for an integrated sustainability assessment of technologies and processes is given. Potential criteria which can be suitable for the evaluation of CO_2 value chains are identified and exemplarily explained.

Experiences of new technologies show that their successful implementation also depends on the acceptance of involved actors and the general public. **Chapter five** presents the results of an own qualitative survey based on freely available German and English documents, studies and publications with the subjects of awareness and acceptance of CO_2 usage. Moreover specific articles, statements, party programs as well as strategy and conference papers are analysed in order to examine attitudes of political decision makers and chosen social actors (e.g. journalists). Based on this analysis, communication lacks are identified and appropriate methods and tools for a successful communication about CO_2 utilisation are proposed.

The final **chapter six** derives recommendations for a appropriate future designing of CO_2 utilisation options out of the results of the previous chapters. The requirements of projects about research and development as well as demonstration are specified. Necessary political and economical aspects about the development of technologies as well as important holistic issues about the ecological tolerance and system integration are identified.

[1] The concrete *performance* of the MCA is not object of this study.

1 Sources of carbon dioxide (CO_2) and hydrogen (H_2)

1.1 Industrial sources of carbon dioxide - qualities, quantities and regional distribution at European level with a special focus on NRW

The power and industrial sectors currently account for almost half of the total GHG emissions in the EU. Many industrial processes like cement production, steelmaking, oil refining or chemical distillation processes, require vast inputs of fuel and energy rich feedstock and cause plenty of CO_2-emissions. The following figure shows the biggest CO_2-sources in Europe, including the emissions for the production of electrical energy. The size of the points represents the amounts of CO_2-emissions. As you can see England, France, Germany and Poland are the countries with the largest and most aggregated CO_2-sources of Europe.

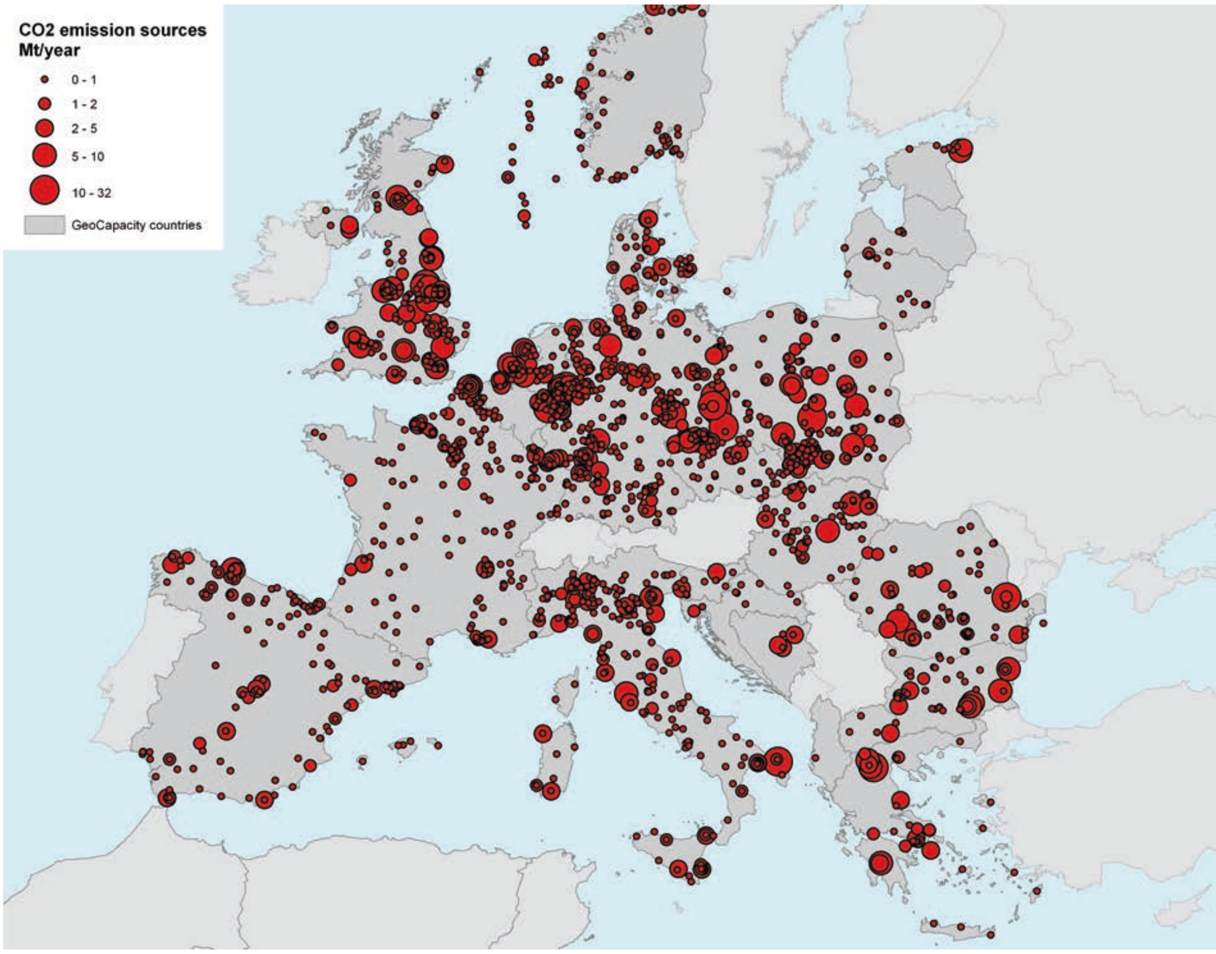

Figure 1-1: CO_2 emission sources in megatons (Mt) per year in Europe
Source: (Geological Survey of Denmark and Greenland (GEUS) 2009)

In 2012 CO_2 emissions from energy use in the EU27 added up to 3.439 gigatons (Gt). The states with the highest level of CO_2 emissions in absolute terms in 2012 were Germany with 728 megatons (Mt), followed by the United Kingdom with 472 Mt, Italy with 366 Mt, France with 332 Mt, Poland with 297 Mt and Spain with 258 Mt. These six States accounted for more than 70 % of total EU27 CO_2 emissions in 2012 (Eurostat 2013).

The following analysis is based on the quantities and qualities of selected industrial and power plants and their flue gas emissions in North-Rhine-Westphalia (NRW). The analysis focuses on those CO_2 sources that will prospectively still exist under a strict future climate protection regime (with a time horizon of about 2030). That implies that we primarily consider industrial sources because their plants and processes cannot easily be substituted by alternative technologies from the vantage point of the present[2]. In the power sector we only look at power plants with low specific CO_2 emissions like waste-to-energy power plants[3] and natural gas and hard coal power plants with combined heat and power (CHP[4]).

The emission sources are characterised by the following criteria:

1. the annual amount of CO_2 emissions,
2. the branch of the industrial emission sources and
3. the purity of CO_2.

Due to economies of scale and to keep the clearness in the figures we set a minimum threshold of 0.4 Mt of CO_2 in the 2012 data of the PRTR register (PRTR 2012)[5]. Nevertheless may smaller plants probably also be suitable for CO_2 utilisation projects, especially in early (pilot) states. Favourable conditions for even smaller CO_2 reuse projects are a high purity of CO_2 in the flue gas, a connection to an existing gas infrastructure or a CO_2 needing process nearby.

The total energy related emissions of CO_2 in NRW are aggregated to 286.8 Mt in 2012, the industrial share accounts for 51.5 Mt or 18 % (LANUV NRW 2014). Figure 1-2 shows all industrial CO_2 emission sources with a yearly output of more than 0.4 megatons (Mt) by branch. In total they amount for 42.4 Mt in 2012 equivalent to 82 % of the total industrial emissions in NRW. The selected industrial plants include the chemical branch, coke ovens, the iron and steel industry, the cement and lime industry and refinieries. The figure also shows waste-to-energy power plants as well as hard coal and natural gas fired power plants with combined heat and power (CHP), which emitted 46.0 Mt CO_2. Most plants are located along the Rhine-area and in the Ruhr-area with the exception of one hard coal CHP plant in Ibbenbüren and the cement and lime facilities in the district of Soest in the eastern part of NRW.

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2 This assumption applies especially for *process*-related CO_2 emissions. But also the potential to reduce *energy*-related emissions (burning of fuels) are limited as the energy efficiency potentials in the energy intensive industry are already tapped for the most part.

3 In Germany the renewable energy share of waste-to-energy plants is set on 50 % by convention.

4 It can be assumed that the CHP plants will still exist in the coming decades because they are crucial for the (district) heat supply of many big cities. Nevertheless, the mix of their fuels and technologies will change towards lower specific CO_2 emissions e.g. by the introduction of geothermal or solar energy or by Power-to-Heat from renewable electricity. We assume that to meet CO_2 reduction targets “dirty” plants will go out of the market at first when CCS is not allowed.

5 PRTR: The Pollutant Release and Transport Register is an Open Data platform on the Internet which features a compilation of information about pollutants’ releases, the disposal of waste and emissions from diffuse sources. It allows users to search for facilities to see data on emissions released into the air and/or water by pollutants and sectors and waste generated through industrial activities.

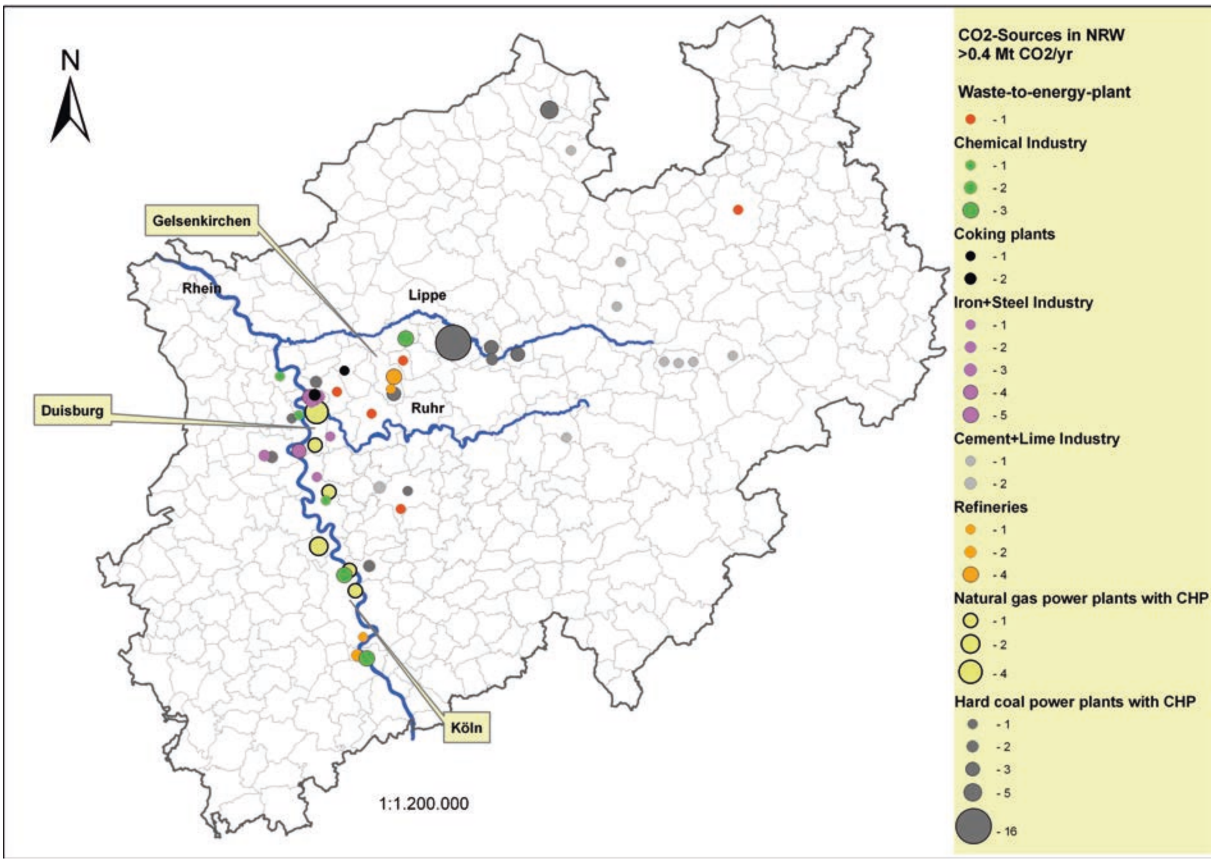


Figure 1-2: Selected CO_2 emission sources from industrial, waste-to-energy and CHP plants > 0.4 Mt/year in NRW

Source: Own figure

The following table compiles the total CO_2 emissions (in Mt/a), the coverage of CO_2 emissions (in %), the numbers of plants, the medial CO_2 concentration in the flue gas and the spatial focus of each branch. By selecting an emission threshold of at least 0.4 Mt CO_2 per year, a high percentage of the total CO_2 emissions in the respective branches in NRW is covererd[6].

[6] For biomethane upgrading plants (see excursus in chapter 1.2) no such threshold was set, because with an average CO_2 release of 0.0036 Mt/a they are much smaller compared to industrial or power plants.

Table 1-1: Overview of the selected branches and the key aspects considered by the analysis (State: 2012)

Branch	**Total CO_2 emissions in Mt/a**	**Coverage of CO_2 emissions in %**	**Numbers of plants**	**Medial CO_2 concentration in the flue gas**	**Spatial focus**
Iron and steel industry	14.8	91 %	6	3 - 27 %	Duisburg and surrounding cities
Refineries	8.1	100 %	4	3 - 13 %	Cologne area and Gelsenkirchen
Chemical industry	9.3	75 %	6	up to 100 %*	Alongside the River Rhine, cities of Gelsenkirchen and Marl
Cement and lime industry	7.9	86 %	10	25 %	District of Soest
Coking plants	2.3	100 %	2	1 - 5.4 % for coke oven gas 3 - 4 % for natural gas underfiring	Duisburg and Bottrop
Industrial Plants	**42.4**	**-**	**31**	**1 - 100 %**	**-**
CHP power plant (hard coal)	35.3	78 %	11	14 %	Between the rivers Lippe and Ruhr
CHP power plant (natural gas)	8.0	94 %	6	3-4 %	Alongside the River Rhine
Waste-to-energy power plant	2.7	50 %	5	14 %	None
CHP & Waste-to-energy power plants	**46.0**	**-**	**22**	**3 - 14 %**	**-**
Biomethane upgrade plants	**0.0417**	**100 %**	**12**	**40-44 %** (in the raw biogas)	Western part of NRW

* e.g. ethylene oxide- and NH_3 production

Source: (PRTR 2012), (Öko-Institut e.V 2012 p. 26), (Dechema 2008 p. 7), (UBA 2012 p. 30), (Dena 2013) and own estimates

In the chemical branch the purity of the CO_2 emissions can reach 100 % (e.g. for ammonia- or ethylene oxide-production). In coke ovens the share of CO_2 in the coke oven gas is between 1 to 5.4 %. But the relevant emissions balanced here originate from the underfiring process where natural gas is burned with typical CO_2 concentrations in the flue gas of 3 - 4%. In spite of these low CO_2 concentrations those emission sources are basically interesting because of their high shares of H_2 and CH_4 and the smaller share of CO. In the iron and steel industry the share of CO_2 depends on the process and the energy source – blast furnace gas has up to 27 % CO_2, if natural gas will be used the CO_2 emissions in the flue gas is only about 3-4 %. In the cement and lime industry the share of CO_2 in the flue gas is about 25 %. The concentration of CO_2 in the flue gas of waste-to-energy plants and hard coal CHP-plants is about 14 %, in the flue gas of CHP natural gas plants the concentration of CO_2 is between 3 to 4 % (UBA 2012).

To conclude in NRW there is a theoretically potential of yearly CO_2 volume flows in the order of 42.4 Mt in the industrial sector (plant sizes > 0.4 Mt) and further 46 Mt from CHP and waste-to-energy power plants (> 0.4 Mt). Additionally biomethane upgrade plants could in total deliver ca. 41,700 t/a. However, although at first sight this seems to be a negligible order, those plants may be principally of interest, because they

- have a high CO_2 concentration in the gas flow,
- are based on renewable energies and
- have the process of CO_2 capture already integrated.

Due to those advantages the biomethane upgrade plants are dealt with in the following excursus (chapter 1.2). Nevertheless due to economy of scale those small plants may rather be suitable for pilot applications of CO_2 utilisation.

1.2 Excursus: CO_2 as byproduct of biomethane plants

Biogas is produced in Germany via fermentation of energy crops or agricultural, domestic or industrial residues. The raw gas contains of about 40 % to 45 % of CO_2 (see Table 1-2) and is normally used onsite for the production of electricity and heat in CHP plants.

Table 1-2: Composition of biomethane in dependency of substrate used

Vol.-%	Energy Crops	Liquid manure
CH4	53	57
CO2	43.7	39.7
H2O	2.31	2.31
N2, H2, O2, H2S	0.99	0.99

Source: (Urban et al. 2008)

Biogas – and biomethane – additionally contain a long list of minor components. It has to be checked, whether there remain minor components as well in the CO_2 stream after separation and in how far they are relevant to what kind of on-going process of CO_2 usage.

If the product gas shall be used not only on-site for the local production of power and heat, biogas can be upgraded to biomethane: if the gas gains the same composition as natural gas (see Figure 1-3), it can be fed into the natural gas grid and thus transported, stored and used at different locations further away.

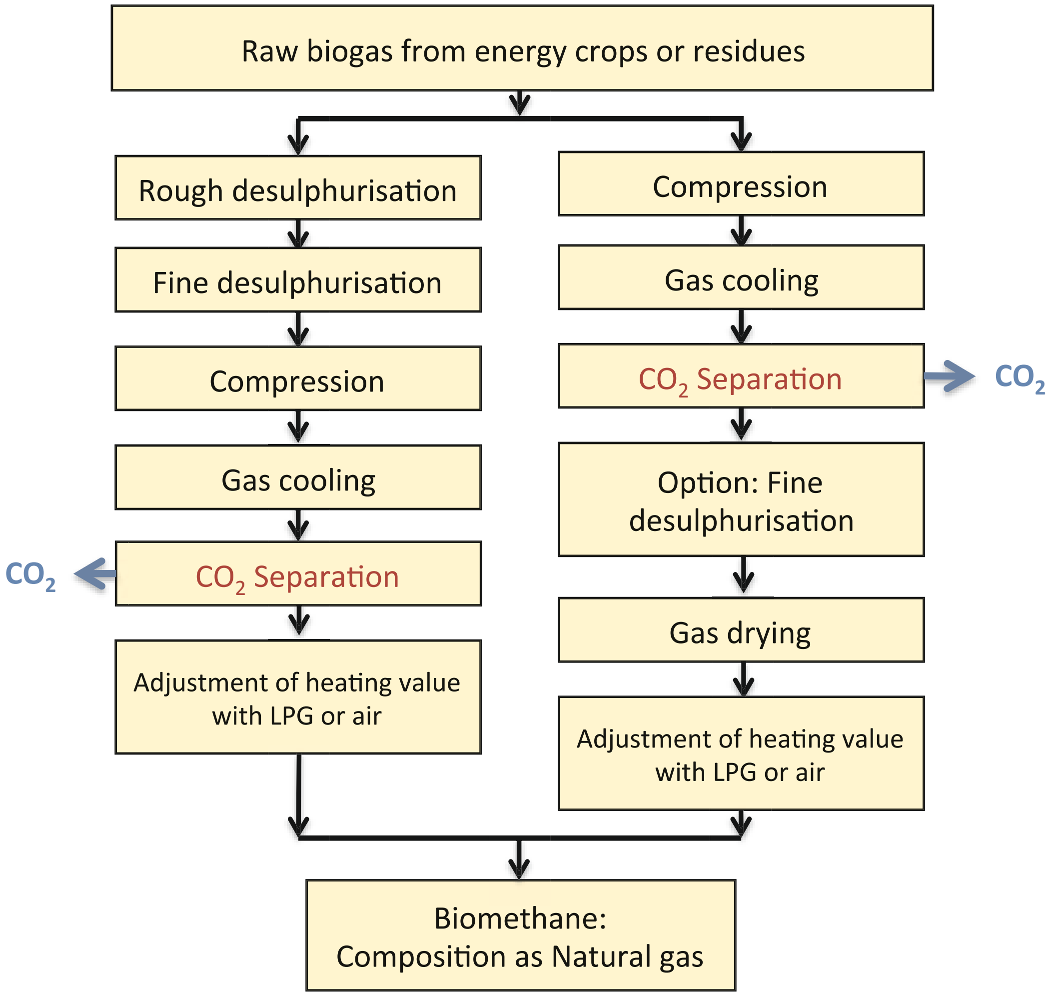


Figure 1-3: Process steps for the upgrading of biogas to biomethane (two different methods)

Source: Own presentation, based on (Urban et al. 2008)

The separation of CO_2 is an important part of the upgrading process, where today the CO_2 is blown off to the air. When using energy crops, emissions of CO_2 during the upgrading process as well as emissions caused by burning of biomethane (following the reaction CH_4 + 2 O_2 -> CO_2 + 2 H_2O) is the same amount, as the plant has taken from the air during its growing period. Hence this amount of CO_2 does not have to be counted with in a greenhouse gas balance.

For clarification: Hereby is not meant the CO_2 deriving from the input of fossil energy in the upstream chain of the production of biogas / biomethane (e.g. used for electricity for pumps, compressors etc.). The successional calculation follows a diverging approach and is not appropriate for a Life-Cycle-Analysis (LCA) of biomethane (as it is for example done in (Arnold 2010, 2011)

The calculation of the amount of separated CO_2 from biomethane is based on the following data (Arnold 2012):

- Mol density of CO_2: 1.977 g/l
- Share of CO_2 in raw biogas: 39.7% / 43.7% (depending on the feedstock; see Table 1-2)
- Separation rate of CO_2: 95%

The separation rate is an own estimation that needs to be validated. Data is not easily to obtain, as most operators of separation units lay focus on the separation and purity of *methane*, not CO_2 as a by-product. The quality of CO_2 produced has to be checked, depending on the chosen separation technology. State of the art are three different types of **separation technologies**:

- Pressure swing adsorption (PSA),
- Pressurized water scrubbing (German: DWW, Druckwasserwäsche) and
- Chemical-physical gas scrubbing (e.g. amine scrubbing).

In North Rhine-Westphalia, one third of all upgrading plants use the PSA and amine scrubbing, respectively. Slightly less applied is the pressurized water scrubbing with 25 % (rest to 100 %: not specified).

The calculation results in an amount of CO_2 separated from biomethane as follows (see Table 1-3):

Table 1-3: Resulting amounts of CO_2 separated from biomethane

Based on...	**CO_2 emissions per energy unit [g CO_2 per kWh CH_4]**	**CO_2 emissions per volume [g CO_2 per m^3 CH_4]**
energy crops	82	820.5
liquid manure	74	745.0

Figure 1-4 shows the amount of CO_2 separated from the biomethane upgrading plants in North Rhine-Westphalia which is in a range of 1,000 to 8,000 tonnes per year (average: 3,550 t/a). Before 2014 there were ten bio-methane plants already in commission with a total annual CO_2 output of 35,600 t rounded, two others (ca. 6,100 t/a) have been under construction in Bergheim near Cologne. In total all twelve plants separate ca. 41,700 t CO_2 per year. Due to the new regulation within the Renewable-Energy-Law (EEG) from 2014, a further expansion of upgrading plants from biogas to biomethane is not anticipated.

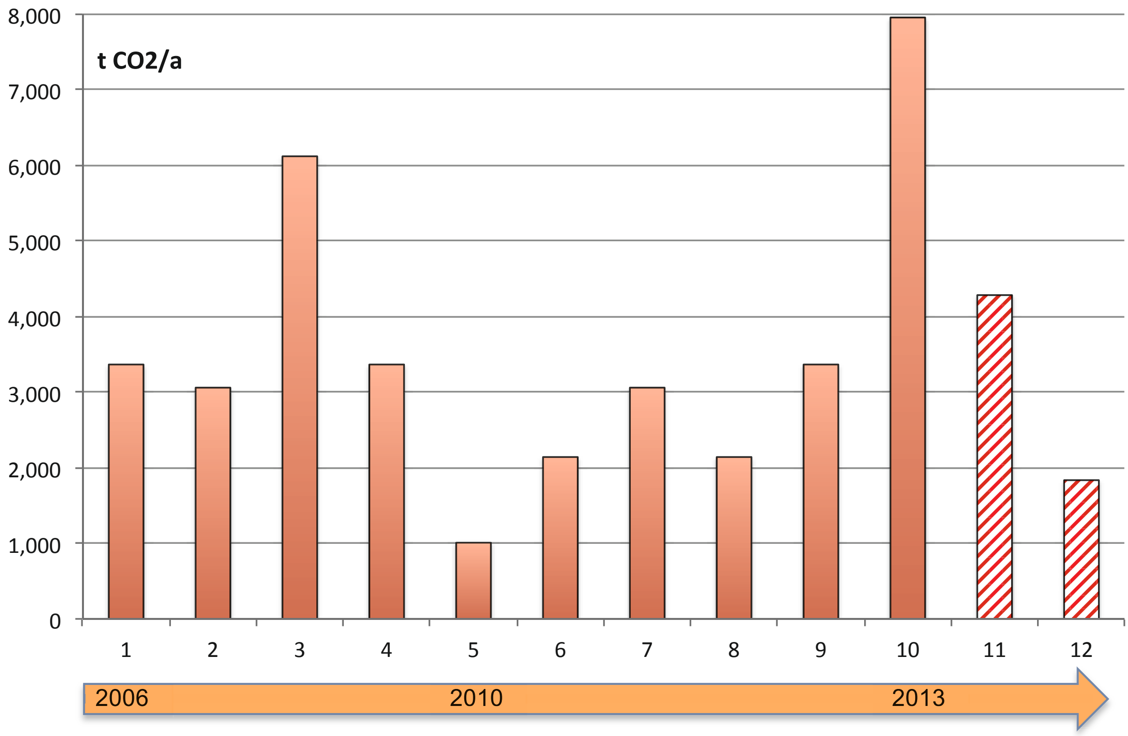


Figure 1-4: Yearly amounts of CO_2 separated from biomethane upgrading units in NRW, sorted by the age of plant, hatched bars: plant in planning & construction

Source: Own results and presentation, based on data according to (Dena 2013)

The spatial spreading of plants is depicted in the map in Figure 1-5. Apart from two units all gas treatment plants are located in the western side of North-Rhine-Westphalia. A further local concentration cannot be identified.

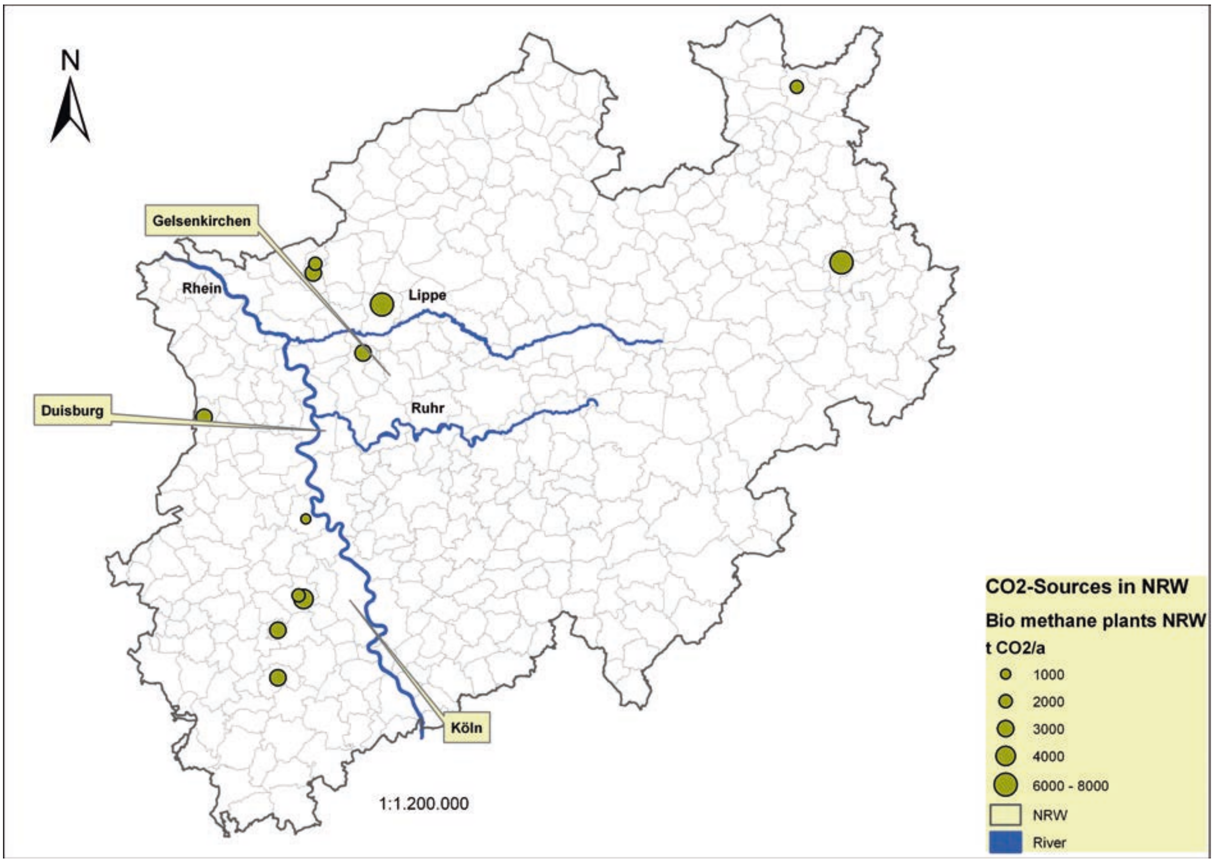


Figure 1-5: Map of biomethane plants with separated (and emitted) CO_2 from the upgrading process

The volume flows of CO_2 from biomethane upgrading plants are about a factor of 100 smaller than from other sources such as industrial or power plants. It has to be checked, if the advantage of obtaining a relatively pure stream of CO_2 from a renewable feedstock is worth the effort of collecting and transporting the small amounts.

1.3 Industrial sources of hydrogen - qualities, quantities and regional distribution at European level with a special focus on NRW

Hydrogen partly results from processes in industry as a by-product and has been used in industry as a chemical feedstock or energy carrier for a long time. Most of that hydrogen is based on fossil fuels, resulting from refining crude oil or coke production. Apart from this industrial origin, hydrogen is produced for other processes from natural gas using steam methane reformers and from heavy oil residues. A fraction of total industrial hydrogen is a by-product of chlorine production using electrolysers, where the carbon intensity depends on the fuel mix in electricity production and namely the share of renewable electricity.

Table 1-4: Properties of various hydrogen production processes

Primary Method	Process	Feedstock	Energy
Thermal	Steam Reformation	Natural Gas	High temperature steam (fossil)
	Thermochemical Water Splitting	Water	Concentrated solar radiation
	Gasification	Coal, Biomass	Steam and oxygen at high temperature and pressure (fossil)

	Pyrolysis	Biomass	Moderately hot steam (fossil)
Electrochemical	Electrolysis	Water	Electricity from renewable energy sources (wind, solar, hydro...)
	Chlorine Electrolysis	Water, sodium chloride/ water, hydrochloric acid	Electricity from fossil energy sources / energy mix (coal, natural gas...)
	Photoelectrochemical	Water	Direct sunlight
Biological	Photobiological	Water and algae strains	Direct sunlight
	Anaerobic Digestion	Biomass	High temperature heat (fossil)
	Fermentative Micro-organisms	Biomass	High temperature heat (solar)

Source: Adapted from various sources: (Fischedick and Pastowski 2010), (Pastowski and Grube 2010), (Ogden and Williams 1989), (Winter and Nitsch 1988)

The most important processes that involve hydrogen in industry are:

- Refineries that handle varying qualities of crude oil in several processes (hydrocrackers, hydrotreating and catalytic reforming) involving hydrogen to produce varying ranges and volumes of final products (hydrogen purity depending on subprocess considered)
- Coke ovens where hydrogen-rich coke oven gas is a by-product (coke oven gas with a relatively low content of hydrogen)
- Electrolysers deployed for chlorine production where hydrogen is usually a by-product (very high level of hydrogen purity)
- Other processes that need hydrogen as a feedstock and where - owing to a lack of nearby other sources of hydrogen - steam methane reformers are used for production (high levels of hydrogen purity depending on kind of use)

Refineries have been net hydrogen producers for quite some time but have turned into net hydrogen consumers owing to decreasing qualities of crude oil and the need to use hydrogen for the desulphurisation of fuels. (CONCAWE 2007)

Coke ovens have for the most of it been closed down in Europe resulting from technical change in steel works and the remaining coke ovens are often integrated with steel production in a way that the hydrogen rich coke oven gas is being used within the overall plant for various purposes. Some of that coke oven gas might be used for other purposes, provided natural gas can serve as a substitute. However coke oven gas may require substantial further processing owing to the relatively low level of hydrogen content.

Chlorine production can be retrofitted with an electrode technology that enables a direct reaction of brine or hydrochloric acid to caustic soda and chlorine without hydrogen being developed, resulting in 30 percent less electricity consumption. The implementation of this technology has just started and may be limited by the need to use hydrogen as a feedstock and an increasing willingness to pay for it.

Other industrial processes co-producing hydrogen are naphta steam cracking, styrol and acetylene production.

Aside from these traditional industrial processes there are other processes for producing hydrogen at varying stages of development which have a focus on hydrogen for energy use. Once hydrogen will be produced in big quantities from renewable electricity for storing and delivering energy, a fraction of this may be used as a feedstock for chemical processes. To day such processes are realized at a small technical size, scale-up to larger scales is still under development and lack broad market introduction. Table 1-4 shows what processes might be used in future to produce large quantities of hydrogen from renewable energy.

Basically, the intensified interest in hydrogen outside usually associated industrial processes was started by activities to bring fuel cell propelled vehicles to the market. When this began in the 1980s[7], quite a bit of industrial hydrogen was still vented off into the atmosphere. This increased the interest in this source of energy that appeared to be both readily available and cheap. However in the meantime, energy prices have been on the rise and there have been increasing efforts to find customers for surplus hydrogen as a feedstock or to at least to use it as a source of energy.

It has also primarily been the intensified interest in fuel cell propelled vehicles that resulted in studies on behalf of the European Commission and North Rhine-Westphalia that have taken stock of industrial hydrogen.

Roads2HyCom was an Integrated Project supported by the European Commission's Framework Programme Six (FP6), Priority 6.1 "Sustainable Development, Global Change and Ecosystems". It was designed to work as a techno-socio-economic research project acting as a planning support and stakeholder outreach instrument for the European Commission and the Joint Technology Initiative. Its purpose was to assess and monitor hydrogen and fuel cell technologies for stationary and mobile energy applications.

Figure 1-6 shows the hydrogen production sites in Europe that have been identified in the Roads2HyCom-Project. As the map reveals, industrial hydrogen production sites can be found all over Europe with somewhat lower concentrations in Northern Europe, Ireland and France. As was to be expected, production sites are spatially concentrated in those areas of Europe where industrial activity is particularly strong.

[7] (Ogden and Williams 1989), (Zittel and Bünger 1995)

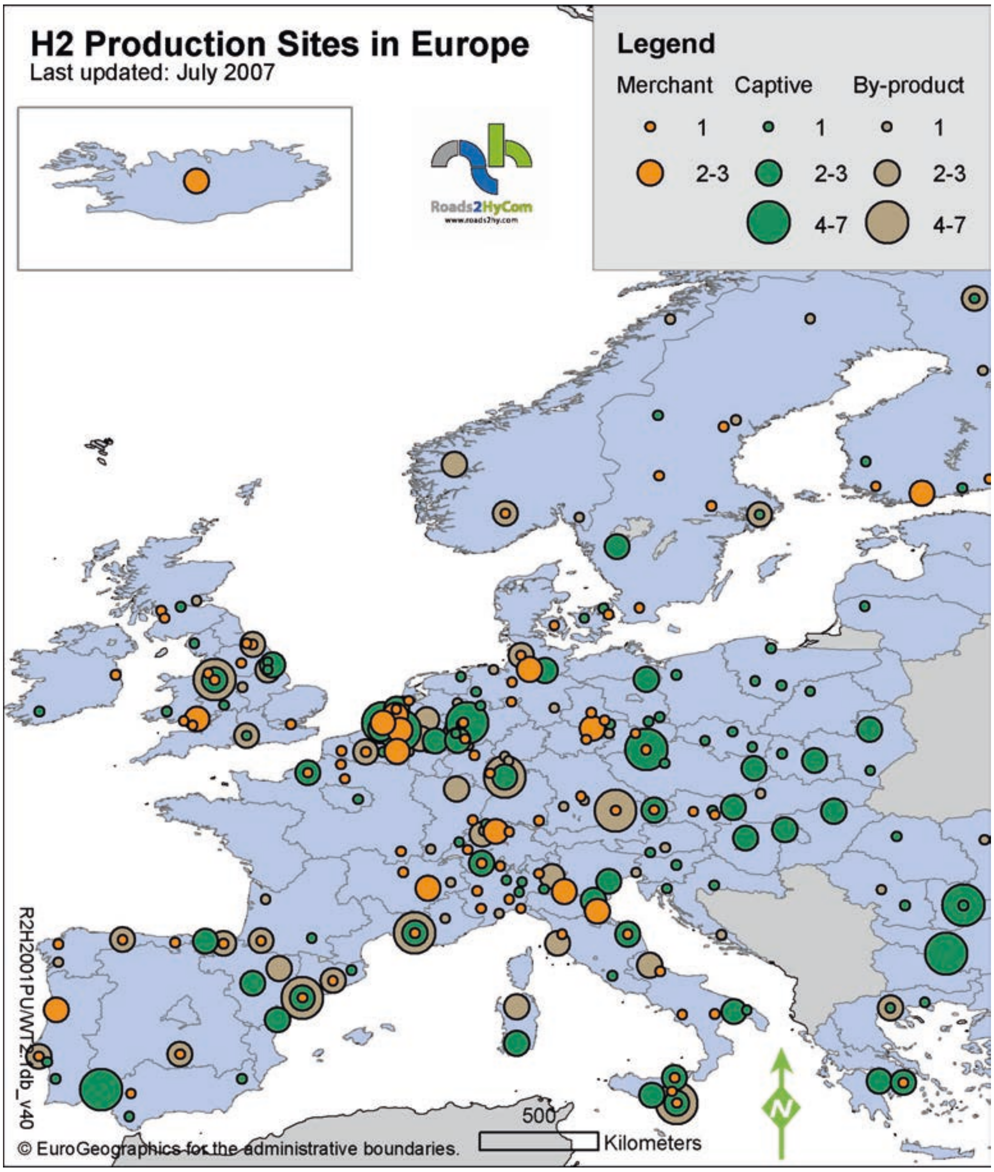


Figure 1-6: Industrial sources of hydrogen and breakdown by use category

Source: Roads2HyCom (Maisonnier et al. 2007)

Three categories of hydrogen are depicted: Merchant, captive and by-product hydrogen. **Merchant hydrogen** is produced using steam methane reformers onsite or in neighbouring plants for other users who require that hydrogen as an input. Moreover it can be traded as smaller specified volumes and transported by road and rail. The most important hydrogen merchants in Europe are the suppliers of industrial gases Air Products, Air Liquide, Praxair, and Linde Gas.

Captive hydrogen is mostly produced by the owners of the plants which use the hydrogen. However, outsourced on-site production of hydrogen by merchants can often be regarded to be as captive. The main difference is who produces the hydrogen that is dedicated as an input to specified production sites.

The third category is **by-product hydrogen** that differs from the other categories in that it is produced in one process but not needed for further steps of the same overall production process of a site. By-product hydrogen appears to be more likely to be made available for other applications because hydrogen from the other categories is bound to particular uses via ownership of production plants or contracts with merchants. However most by-product hydrogen is currently used too. Within the chemical industry hydrogen is used for chemical processes (hydrogenation e.g.). Partly it is used for process heat or to generate electricity, especially in steel industry, and this fraction could be replaced by natural gas provided this can easily be made available.

Apart from the origins and original purposes of industrial hydrogen, the layouts of new production sites are often designed in a way to make use of everything that is produced. Notwithstanding this, as hydrogen is an energy carrier it may always be used to produce process heat or electricity with minor changes in plant layout.

The project **H2NRW** was an effort to take a deeper look into the production and distribution of industrial hydrogen in the state of North Rhine-Westphalia. It aimed at assessing potential hydrogen volumes that might be used to fuel an initial fleet of fuel cell vehicles before renewable sources of hydrogen might be put in place. Moreover the industrial supply infrastructure of hydrogen was considered as a potential stepping stone towards a universal system of hydrogen supply. In order to gather the necessary information, H2NRW included the identification of relevant plants and sites within North Rhine-Westphalia and a new survey that allowed to establish current production volumes. The map depicted in Figure 1-7 and the illustration in Figure 1-8 show some of the results of the H2NRW project.

Table 1-5: Results of the H2NRW project

	Total H_2 in kNm^3/d	**Available H_2 in kNm^3/d**	**Available/Total in %**
All plants	10 786	958	9
Chlorine	1 732	810	47
Refineries	3 363	56	2
Others	5 691	92	2

Source: Based on findings of the H2NRW project (Fischedick and Pastowski 2010), (Fischedick et al. 2009)

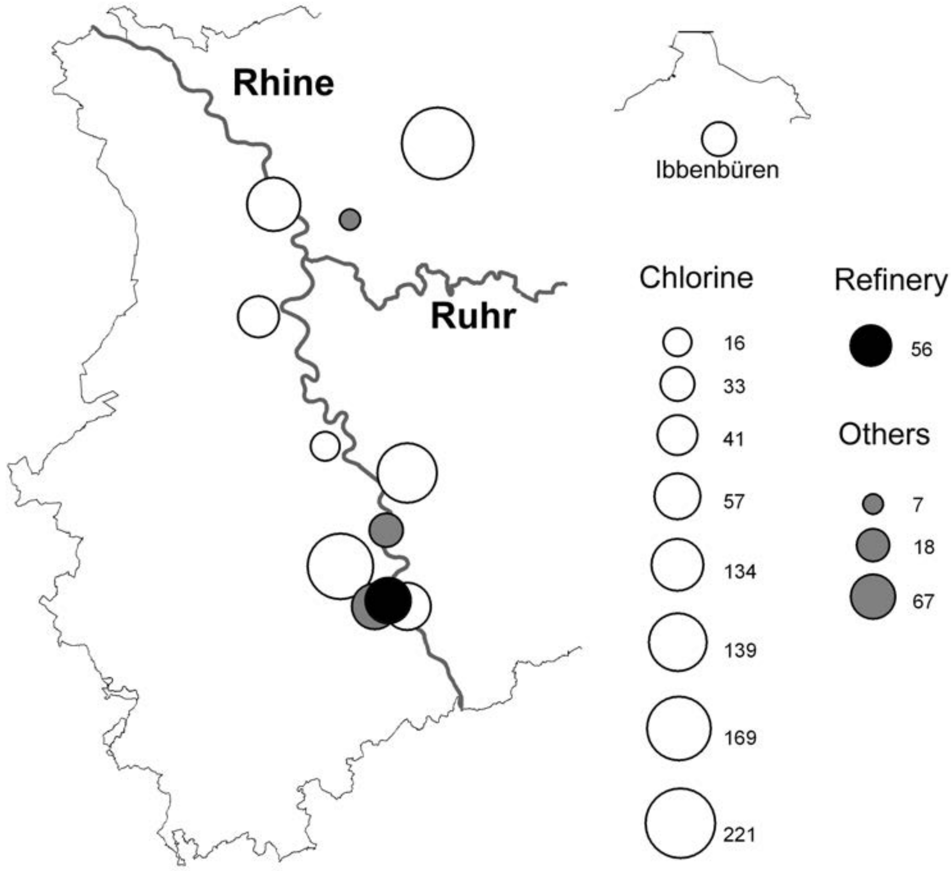


Figure 1-7: Potentially available industrial hydrogen in NRW as of 2008 (1000 Nm^3 per day), Source: Based on findings of the H2NRW project (Fischedick and Pastowski 2010), (Fischedick et al. 2009)

It is no surprise that most of the hydrogen that was identified as potentially available for other use in the H2NRW project resided as a by-product at the chlorine industry. At that time there was still some potential at one out of three refineries. Two coke oven plants had reported no potential because those and their gas were fully integrated in combined coke oven and steel works while one had some coke oven gas available. In general the companies aspire to use the coke oven gas internally and legal framework is designed to promote self-sufficiency. But this might not be the most resource efficient solution in any case.

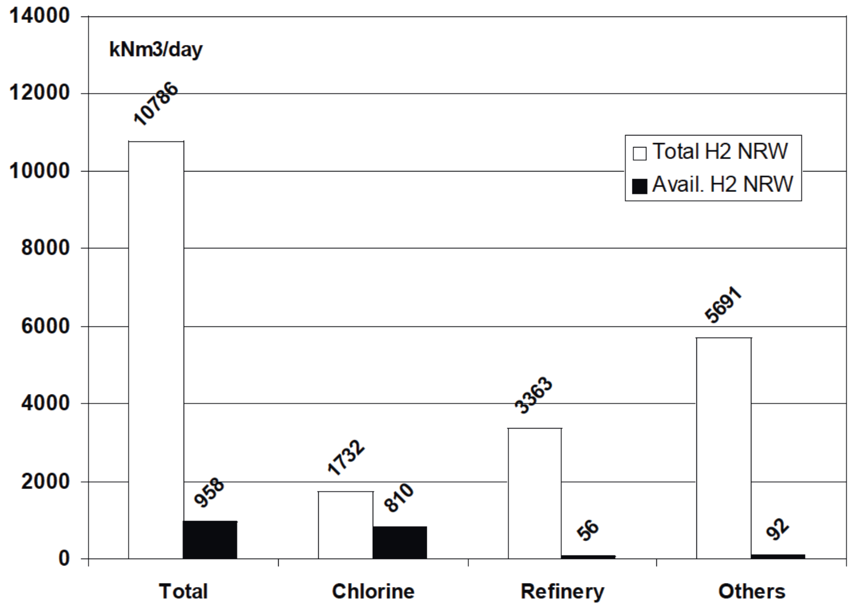


Figure 1-8: Total production and potentially available hydrogen in North Rhine-Westphalia by industry as of 2008
Source: Based on findings of the H2NRW project (Fischedick and Pastowski 2010), (Fischedick et al. 2009)

For the purposes of this study a new query with related plants in North Rhine-Westphalia has been performed that built on previous work on this matter. Figure 1-9 shows the questionnaire that delivered site-specific data based on the H2NRW or the Roads2HyCom projects and asked for current data of the same kind. This was meant to remind the respondents what numbers had been provided for the H2NRW project (or Roads2HyCom respectively). Moreover the intention was to make clear that data on the volume of hydrogen production and the breakdown of its use by category did already exist. Besides some explanations were provided as to the purpose of this query within the Climate-KIC context.

The questionnaire and other material was finalised in early November 2014 and all sites that had taken part in the H2NRW project were immediately contacted by telephone in order to pave the way for the query and to identify company or site-specific staff responsible for it. After this the questionnaire was sent to the identified staff by e-mail. Most of the response has been finalised by December 12 2014, while just a few replies have been obtained in early January 2015.

Generally, the response was good but some of it lacks sufficient detail. Three chlorine production sites from one company have neither delivered current data on production volumes nor on the structure of its current use. Owing to the high share of these sites in total chlorine production, this lack of data has made a comprehensive interpretation of changes over the state depicted by the project H2NRW impossible.

Wuppertal Institut für Klima, Umwelt, Energie GmbH

Aktualisierung Industriewasserstoff NRW im Rahmen von Climate-KIC

Standort		2008	2014
Eigentümer			
Prozess			
R2HyC	kNm3/d		
H2NRW	kNm3/d		
Tage/Jahr	d/y		
Reinheit	%		
Druck	Bar		
Input	%		
energetisch	%		
Verkauf	%		
Abg. ü. Dach	%		
Bemerkungen 2008			
Bemerkungen 2014			

Figure 1-9: Questionnaire on total production and breakdown of hydrogen by use category

Source: Wuppertal Institute

Hence it is only possible to deliver conclusions on other production processes and separately for the chlorine production sites that provided a complete response and those that did not. While some of the respondents have asked for non delivery of any site-specific data, the interpretation of the data obtained cannot be the same as with the H2NRW project. It therefore only provides conclusions at certain aggregate levels.

Total hydrogen production in North Rhine-Westphalia included in this update is substantially smaller compared to the volumes reported in the H2NRW project (7 766 kNm^3/d instead of 10 768 kNm^3/d). This mainly results from the three chlorine production sites, two refineries and two other production processes delivering no data. Therefore it is difficult to assess whether total industrial hydrogen production in North Rhine-Westphalia has risen or shrunk. However those sites, that responded, mostly have kept daily production stable except for two refineries that have substantially increased production. Owing to the sites that did not respond, changes in total production cannot be estimated or explained based on the survey.

An estimate of total hydrogen volumes from chlorine production in NRW based on chlorine output of 1 442.5 kilotons in 2013 in 2013 results in 1 277 kNm^3/d which is 26% less than what had been found in the H2NRW project (1 732 kNm^3/d in 2008).

Apart from total production volumes another focus of the survey was placed on the breakdown of total hydrogen produced by use category. Here the three incompletely responding chlorine production sites have delivered some information.

Hydrogen produced by these three chlorine production sites is primarily used for hydrogenation within the company or by external partners on the same sites. Capacities of production and use have been balanced to an extent that no hydrogen is available for other sites.

Remaining variation in production and need of hydrogen is usually buffered using the Air Liquide pipeline and in the scarce instance that the capacity of the pipeline is insufficient some hydrogen may be used as an energy carrier.

This appears to be a substantial change over the situation described by the H2NRW project, where venting off still made up some 4 to 11 per cent of production and energetic utilisation varied from 0 to 27 per cent. The increase in use as a chemical input with the plants that failed to provide detailed figures is somewhat in contrast to information that has been obtained from the other sites of chlorine production, where changes in this category are less substantial and more varied. However this may reflect increased efforts at those plants to raise the use of hydrogen as a chemical feedstock.

From the responses of the chlorine production sites reporting sufficient data the following conclusions can be drawn:

Notwithstanding the three chlorine production sites that did not deliver data on hydrogen production, only one out of the five sites included in the survey has reported slightly lower production while hydrogen production volumes have remained the same for four of them.

Generally, the venting off of hydrogen has substantially been reduced and has only been reported from three sites of chlorine production. However it remains to be somewhat unclear how this has exactly developed with the chlorine production sites that did not fully respond as there was no mention of this in their response.

With regard to purity of the industrial hydrogen considered it can be stated that this has not changed for most production sites. The highest levels of purity are achieved in chlorine production (up to 99.99 per cent) and where hydrogen is produced using steam methane reformers (up to 99.95 per cent). The only higher levels of purity as compared to the results of the H2NRW project can be reported for two refineries that have at the same time substantially increased their production capacity. However refineries have turned into net hydrogen consumers and it is therefore very unlikely that those may provide hydrogen for other use.

Conclusions:

Most industrial hydrogen is only produced to be used as an input for the chemical industry. Therefore, it is unavailable for other use. Volumes of hydrogen available for other use can theoretically be identified as excess production capacity that depends on capacity utilisation of related plants and maintenance. Therefore, excess capacity of hydrogen production is very limited, hard to track and may be important for phases of economic prosperity and for growth of the industry which has set up the production site or which has got long term contractual arrangements for delivery. The willingness to provide limited volumes of hydrogen from such sources might therefore be restricted to economical feasible market prizes and pay-back time of investments that have to be undertaken to guarantee the supply out of the industrial network.

Another category is by-product hydrogen for the most of it from chlorine production that is currently not used or used as an energy carrier that could be substituted by natural gas or other fuels. In principle, by-product hydrogen offers the greatest potential to make contributions to the supply as a chemical feedstock.

The most reasonable category for other use may be hydrogen that is vented off into the atmosphere. This category has substantially declined during the last decades.

The volumes of hydrogen identified in the H2NRW project from 2008 as being theoretically available for other use had to be based on simplifying assumptions concerning the availability of hydrogen used for other purposes than as a feedstock. Those included that hydrogen vented off may be stored and that hydrogen used as an energy carrier may be substituted by natural gas. The availability of merchant hydrogen is difficult because it is currently used for other purposes. In fact existing contracts for hydrogen delivery may preclude other use of that hydrogen at least until such contracts terminate.

Nevertheless for very early and small volume applications all industrial sources of hydrogen may be considered primarily based on quantitative (volume) and qualitative (purity) criteria. For this purpose it is useful to take stock of all existing sources of industrial hydrogen of a region considered for the location of early applications. It is clear that the extent of available by-product hydrogen depends on the industrial structure and is therefore subject to substantial variety.

1.4 Milestone: Overview of CO_2 and H_2 sources

Prospectively 88.4 Mt CO_2/a will be available in North-Rhine Westphalia in the mid term until 2030. The current amount of industrial CO_2 sources (> 0.4 Mt/a) in NRW amounts to 42.4 Mt/a. Additionally, 46 Mt/a are emitted from natural gas and hard coal CHP and waste incineration plants (> 0.4 Mt/a). Fossil based power plants without CHP are supposed to be almost phased out and substituted by renewable energies and / or cut down by energy savings until 2030. Industrial emissions will still exist and come from chemical industry, coke ovens, iron and steel industry, cement and lime production and refineries. Four steam crackers in chemical industry are a relevant source with about 3 to 5 Mt CO_2/a and make up 60% of NRW's capacities for ethylene production. In the cement industry, both oxyfuel and amine scrubbing are discussed as techniques for carbon capture for the future[8]. Converter gas and coke oven gas from iron and steel industry contain considerable amounts of CO_2, CO and H_2 and could be used. The sources are mainly situated along the river Rhine and in the Ruhr area. Only cement plants are distributed rather in the eastern part of NRW.

H_2 is produced as by-product from various processes, especially from chlorine electrolysis. It is purified, dried and compressed for transport and offers greatest potential for utilization in future scenarios. Most of the produced 5 Mt H_2/a in Germany is directly produced for use in chemical industry. In NRW, from 350 kilotons of H_2 produced in 2008 (10 786 kNm^3/day), only 31 kilotons of fossil-based H_2 were available for external use (958 kNm^3/day).

[8] Compare (VDZ 2013) for recent research on oxyfuel technology in the cement industry.

2 Utilization options for carbon dioxide (CO_2) and hydrogen (H_2)

2.1 Current utilization structures of CO_2 and H_2 as a feedstock (general overview)

2.1.1 Global industrial use of carbon dioxide

CO_2 is used in a great variety of industrial processes. Utilization of CO_2 is performed in the petroleum sector, during food production, in the beverages industry and in the manufacturing of chemicals and chemical products (Muradov 2014).

In the literature, there are two different types of use mentioned: the *captive* (process-integrated) and the *non-captive* use. **Captive processes** use CO_2 as an intermediate product in the manufacturing chain and do not require CO_2 from external sources (e.g. urea processing is regarded in this category, as the CO_2 is derived from fossil hydrocarbons). **Non-captive** CO_2, in contrast, is used in processes where CO_2 is needed as an external source (Global CCS Institute and Parsons Brinckerhoff 2011). Consequently, non-captive CO_2 is also called merchant CO_2. It is traded via markets and is actually the kind of CO_2 whose demand could rise. Subsequently, the focus of the analysis lies on non-captive CO_2. Nevertheless, also the use of CO_2 in urea processing should be considered, as it could be provided by external sources in the future. Both captive and non-captive use of CO_2 may lead to an integration into final products, and may also be part of a carbon recycling depending on the process chain design.

CO_2 can be used as a feedstock or supplementary in several industrial processes. Most common fields of use are the following physical applications:

- For enhanced oil and gas recovery (EOR / EGR)
- Within the beverage industry
- As a blanket or inert gas, for the food industry and for example for welding
- As a coolant or cryogenic agent (in cars, in supermarket display cases)
- As a cleaning agent in the textile and the electronics industry (e.g. degreasing)
- As a fire fighting foam in fire extinguishers
- In greenhouses as “a plant nutrient”
- Wastewater treatment (neutralization, drinking water abstraction)
- In mechanical processes such as milling, extruding, forming, extractions, and in chemical analytics, as supercritical CO_2
- In applications where solid carbon dioxide snow is needed
- For pest control[9]

[9] www.airliquide.de/inc/dokument.php/standard/911/kohlendioxid.pdf ; Nachrichten aus der Chemie; Alexis Bazzanella, Dennis Krämer, Martina Peters; Nr. 58, Dezember 2010, S.1226 ff.

Total non-captive consumption is estimated at a value of 80 megatons per year (Mt/a) (Global CCS Institute and Parsons Brinckerhoff 2011). A short overview of the quantities used in different utilization processes is given in Table 2-1. With about 50 Mt/a most of the merchant CO_2 is used in Enhanced Oil Recovery (EOR). Globally, the chemical industry, approximately uses 35 Mt/a of non-captive CO_2 (Ritter 2007). Inorganic compounds and pigments need 18.5 Mt/a CO_2 to be manufactured (Zevenhoven et al. 2006). The production of technological fluids (that cannot account for the chemical industry alone) uses 18 Mt/a CO_2 (Aresta and Dibenedetto 2007). Methanol synthesis is the last major use process of CO_2 within the chemical industry and uses 2 Mt/a (Li et al. 2006). Besides these processes the production of polycarbonates (0.4 Mt/a), dimethyl carbonate (<0.1 Mt/a), cyclic carbonates (0.04 Mt/a) and salicylic acid (0.02 Mt/a) contribute to the use of CO_2 (Zevenhoven et al. 2006); (Li et al. 2006); (Ausfelder and Bazzanella 2008).

Table 2-1: Processes of global CO_2 utilization; the values indicate orders of magnitude

Utilization process	Quantity (Mt/a)
Urea production[1]	110
EOR[2]	50
Food processing, preservation and packaging[3]	10
Other liquid CO_2 applications[3]	6
Beverage carbonation[3]	5
Precipitated $CaCO_3$[3]	2
Methanol synthesis (via hydrogen-rich syngas)[4]	2
Oil and gas industry (Other than EOR)[3]	1

[1] Expert guess of Bayer MaterialScience / own estimate
[2] (Global CCS Institute and Parsons Brinckerhoff 2011)
[3] (Muradov 2014) after (Global CCS Institute and Parsons Brinckerhoff 2011)
[4] (Ausfelder and Bazzanella 2008)

For a more detailed listing of the processes see Table A 5 in the Annex.

Figure 2-1 shows basic chemical transformations using CO_2: (a) Urea production, (b) Methanol production, (c) Salicylic acid production, (d) Cyclic carbonate production.

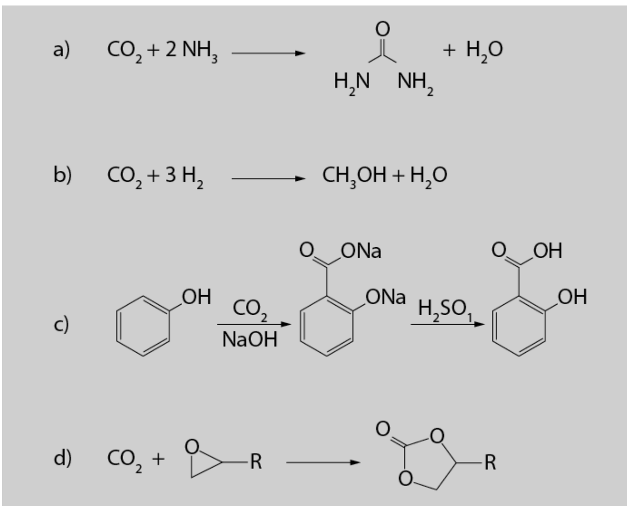


Figure 2-1: Common reactions of CO_2

Source: Own illustration after (Bazzanella et al. 2010 p. 1226 ff.)

In recent years, a lot of research activities have been undertaken to open up the possibility of the use of CO_2 as a feedstock or building block for the chemical industry. The key to carry out the synthesis in a resource and especially energy efficient and therefore cost-effective manner is the development of catalysts that enable the activation of CO_2. Figure 2-2 shows two prominent examples of **co-polymerization** of CO_2 with epoxides to

a) polycarbonates
b) polyether carbonates polyols.

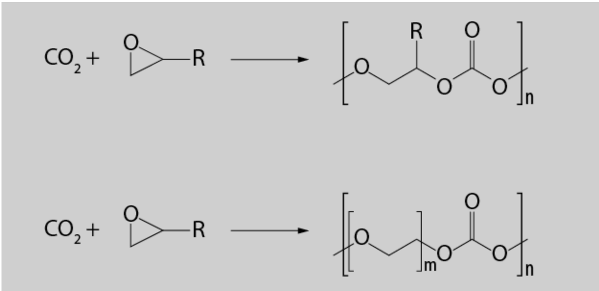


Figure 2-2: Polymers from CO_2

Source: Own illustration after (Bazzanella et al. 2010 p. 1226 ff.)

Most prominent examples of polymer production with CO_2 are the polymers based on catalysts developed by econic[10] as well as a polyether polycarbonate developed by Bayer MaterialScience (BMS). The development of the BMS polymer and its production process has been funded by the German Federal Ministry of Research[11].

From a mid-term perspective scenarios in which CO_2 as a feedstock for methanol plays a crucial role could be of interest for **methanol-based chemistry** in general. Methanol also can be converted into several base or platform chemicals (cf. Figure 2-3).

[10] www.econic-technologies.com/technologies/products/hmw-polycarbonates

[11] www.chemieundco2.de/_media/CO2_2013_Broschuere_web.pdf

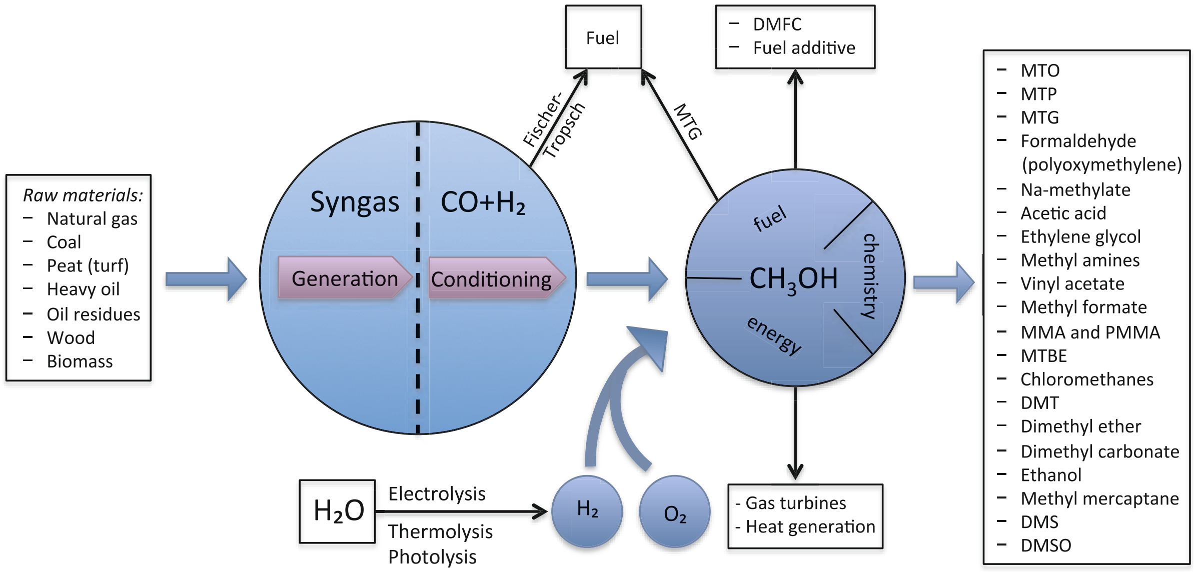


Figure 2-3: Methanol-based chemistry: from raw materials to synthesis gases, methanol, chemicals and fuels

<u>Abbreviations:</u>

DMFC:	direct methanol fuel cell	MTO:	methanol-to-olefins,
MTP:	methanol-to-propylene	MTG:	methanol-to-gasoline
MMA:	Methylmethacrylat	PMMA:	Polymethylmethacrylat
MTBE:	methyl-t-butyl ether	DMT:	Dimethylterephthalat
DMS:	Dimethylsulfat	DMSO:	Dimethylsulfoxid

Source: (Bertau et al. 2014 p. 7) with own changes

Actually, there are some chemicals of economic interest which are derived from methanol, for example formaldehyde, ethylene glycol, di-methyl carbonate. Methanol is of interest for the fuel sector, as methanol itself or as additive, for example converted to dimethyl ether or methyl-t-butyl ether (MTBE)[12]. Perspectively, a broad range of chemicals could be produced. (Bertau et al. 2014 pp. 408–409) gives a detailed survey of methanol chemistry.

Furthermore, CO_2 will be of interest for the **Sabatier-Process** in order to produce **methane**:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$$

Europe possesses an excellent infrastructure in terms of transportation and use of methane (or rather natural gas), so there are established markets and means of transportation like pipelines that could be used.

Especially if methanol or methane is produced from CO_2, there are two main points to be regarded: If in fact a “methanol economy”, as discussed in some scientific circles, would be part of a future society, huge amounts of CO_2 as well as huge amounts of hydrogen will be needed. The same would occur, if Power-to-Gas technologies will be enforced (see chapter 2.3).

2.1.2 Global industrial use of hydrogen

Actually, hydrogen is used mainly for chemical and metallurgical purposes:

[12] anti-knocking agent, reduces tail pipe emissions through improved incineration

- Production of ammonia (Haber-Bosch)
- Hydrogenation (fat hardening, synthesis of anorganic and organic basic chemicals, polymer production, for example toluylene diisocyanate, TDI)
- As a reduction agent in metallurgical processes
- Fuel or energy carrier

The total global amount of H_2 used by industrial processes varies from 41 Mt/a (Suresh et al. 2004) in (Argonne National Laboratory 2003) to 50 Mt/a, or may have been increased accordingly over the past decade (The Essential Chemical Industry online 2015). Referring to (Le Duigou et al. 2011) 7.8 Mt/a of H_2 are used in Europe.

Typically, H_2 is used in larger amounts for producing chemicals (particularly ammonia and methanol) and in refineries for hydrocracking respectively hydrotreating. Lesser quantities are used in steel production, fat and oil hydrogenation, flat glass production, in the electronics industry, for metal processing and in thermal power plants (Stiller 2014). However, 94.6 % of intentionally produced hydrogen is used captively for manufacturing of ammonia (58.5 %), for refinery hydroprocessing operations (25.9 %) and for producing methanol (9.8 %). Only 4.3 % are used as merchant H_2 (Information Handling Services 2007). For total quantities of H_2 utilization by processes Table 2-2 is given.

Table 2-2: Processes of global H_2 utilization

Utilization process	Quantity (Mt/a)
Ammonia synthesis	24
Refinery processes	11
Methanol synthesis	4
Others	0.5
Non-captive uses	1.7
Sum	41.2

Source: (Suresh et al. 2004) qtd. in (Argonne National Laboratory 2003)

More detailed information can be found in Table B in the Annex.

2.2 CO_2 and H_2 as a specific feedstock for the chemical industry

In general, CO_2 and hydrogen that are used in chemical reactions should have the highest possible purity. When reactant flows contain impurities the main reaction yield can be reduced due to side reactions and other inhibition or deactivation mechanisms. Needed specifications of CO_2 and hydrogen as reactant depend on the specific reaction and the used catalyst. So called “catalyst poisons” are particularly critical. These compounds inhibit the desired reactions by blocking the active catalyst sites. Well-known catalyst poisons are heavy metals, halogens, sulphur, carbon monoxide and traces of polymers, for example.

Hydrogen is mainly produced in significant industrial amounts by steam reforming and as a by-product in the chlorine electrolysis. Hydrogen purification and drying processes are necessary for both technologies. After purification and drying hydrogen has to be compressed, in order to be transported. At chemical production sites pipelines are used to transfer hydrogen to the processing factory where it is needed.

Actually many chemical production sites have a lack of sufficient infrastructure for CO_2 supply. Depending on the products needed, CO_2 can be a by-product of steam reforming. In case that CO is the needed reactant, the operation mode of a steam reformer can be adjusted so that no or little CO_2 is produced. The ideal control of reaction process is:

$CH_4 + H_2O \rightarrow CO + 3\ H_2$ (no CO_2 emissions)

The emerging CO_2 will be re-integrated into the process and converted to CO, using hydrogen surplus:

$CO_2 + H_2 \rightarrow CO + H_2O$

Table 2-3: Production volume of hydrogen [billions of Nm^3/a]

	Germany	**World**
Steam reforming of natural gas and naphtha	6	190
Partial oxidation of heavy oil	3	120
Petrochemistry: gasoline refinery	2.5	90
Petrochemistry: ethylene production	3.6	33
Other chemical industry	0.9	7
Chlorine-alkali-electrolysis	0.9	10
Coal gasification (coke gas)	2.1	50
Total	**19**	**500**

Source: German Hydrogen and Fuel Cell Association (DWV)[13]

In cases when hydrogen production needs to be maximized, the re-integration of CO_2 will not be pursued. At chemical production sites most often steam reformers are operated to produce CO as well as hydrogen due to the interlinked downstream productions. Thus re-integration of CO_2 into the reforming process is very common. Furthermore, reforming technologies (like dry reforming) exist where CO_2 is used as the main feedstock to produce CO, by the chemical reaction as shown above. So far, this process cannot be operated in an economic way because of the lack of availability and adequately priced CO_2 and H_2.

2.2.1 Demand and utilization of CO_2-needed quantities and qualities and purpose of use, today and in future times

In 2011 in Germany, 20.7 Mt of plastics were produced, 11.9 Mt were exported, and 8.4 Mt were imported (Consultic 2012). From the 17.2 Mt total input to manufacturing,10.6 Mt consisted of the basic polymers (e.g., PE, PP, PS, polyvinylchloride, and polyamide), whereas the rest were glues, varnishes, resins, fibers, and so forth. Considering that one third of German industrial production is for export, and assuming this holds also for plastic-based final products, that would render 7.1 Mt of polymers for domestic final consumption. Assum-

[13] www.energieportal24.de/cms1/wissensportale/brenn-kraftstoffe/wasserstoff/h2-herstellung, accessed at 19th December 2014

ing an average carbon content of approximately 75%, and neglecting production losses, one would need approximately 5.3 Mt of carbon as a source to produce this amount. Because 1.4 Mt of postconsumer plastic waste was recycled, at least 4 Mt of fossil carbon would be required to supply the domestic demand (Bringezu 2014). If that amount were to be supplied completely on the basis of CO_2, 15 Mt would be required.

2.3 CO_2 and H_2 as a specific feedstock for fuel synthesis (Power-to-Gas/Fuel with renewables)

The general idea of Power-to-Gas (PtG, also: P2G) and Power-to-Fuels (PtF, also P2F; as well Power-to-Liquids; P2L) is the conversion of renewable electricity via electrolysis to hydrogen and/or methane and methanol, respectively. The gas can than be transported via the existing gas grid, including a certain storage option due to the capacity of the grid.

The electricity shall be taken from renewable sources, e.g. wind turbines in times of high supply and low demand, where it cannot be used instantly. Thus, PtG is an option for the comprehensive integration of renewable energy to the overall energy system. As storage option, it can help to balance the fluctuation of wind and solar energy supply.

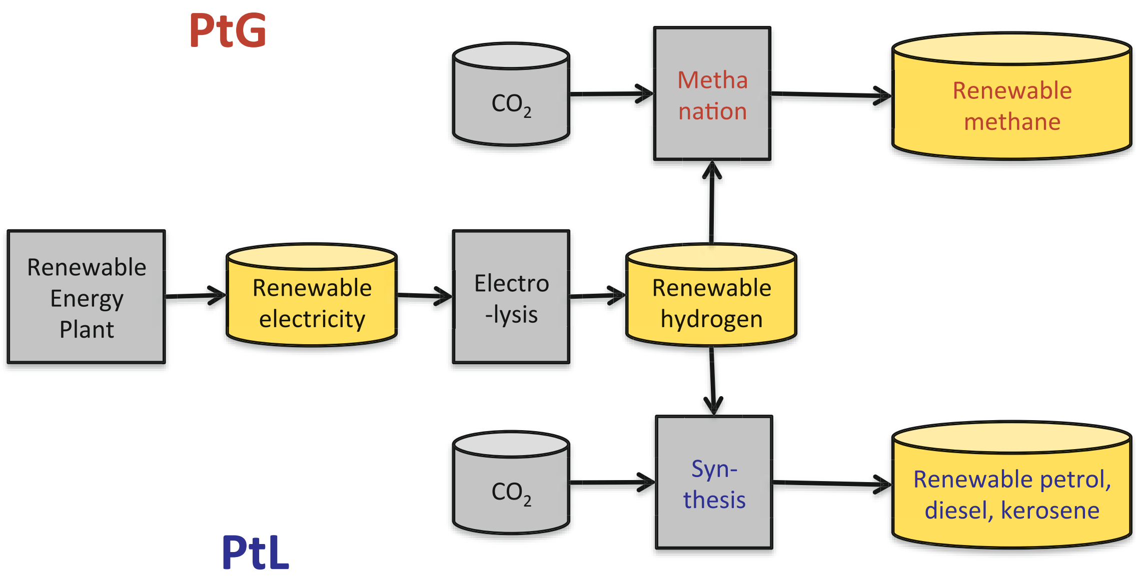


Figure 2-4: Scheme of process chains for Power-to-Gas (PtG) and Power-to-Fuels (PtF) (BMVI 2014)

The process steps of methanation and fuel synthesis are optional, as hydrogen as product from the electrolysis can be either used directly (in different industrial processes, for example in the steel industry) or transported via the natural gas grid, in small amounts up to approximately five or ten per cent of the grid capacity. A number of options for use is possible, all of them with the advantage of being renewably produced:

- Hydrogen for diverse **industrial processes** (steel industry, chemical industry, etc.);
- Fuel (hydrogen, methane or methanol) for the **transport** sector as
- **Chemical** building blocks (methane, methanol, for further processing);
- **Heat** for the industrial as well as the domestic sector as methane;
- **Electricity** via re-electrification of hydrogen in a fuel cell, combined-cycle plant etc. (incl. storage option for electricity)

Relevant technologies for PtG are the electrolysis of electricity to hydrogen (currently done via alkaline water electrolysis, PEM- of SOFC electrolysis) and the chemical reaction of hydrogen and CO_2 to methane (methanation).

A number of studies have been conducted regarding the conversion efficiency of Power-to-Gas. However, in many cases, only the conversion of electricity to hydrogen in the electrolysis is named, thus giving a very positive picture. For a broad view and a better assessment to the concept, the whole process chain up to the use of the produced gas has to be taken into account. Table 2-4 gives average conversion efficiencies for the respective process steps from the electrolysis to the re-electrification. Although the single conversion efficiencies are fairly high, the overall efficiency is just in the range of an average power plant.

Table 2-4: Conversion efficiencies for Power-to-Gas process chain including re-electrification; process chain via hydrogen and methane

	Product: Hydrogen	Product: Methane
Electrolysis (including auxilary plants)	71.3%	71.3%
Methanation	-	80.0%
Compression, Storage, Injection to the grid	98.5%	98.5%
Transport (500 km)	99.6%	99.6%
Re-Electrification (Combined cycle power plant)	50.8%	50.8%
Overall conversion efficiency Power-to-Gas-to-Power	**35.5%**	**28.4%**

Economical analysis have shown, that costs for electricity and investment costs are the most crucial factors for a Power-to-Gas system (BMVI 2014). Wether the product will be economically feasible, depends as well on the choice of use and the respective marktes. The willingness to pay is different for transport fuel (4,7 €/kg H_2 to 9,3 €/kg H_2, according to (BMVI 2014)), for industry feedstocks (2,5 €/kg H_2 to 4,5 €/kg H_2) and for the re-electrification in the power sector (1,6 €/kg H_2 to 3,1 €/kg H_2).

For a number of seven P2G projects, the specific investment costs have been listed and analysed by (Graf et al. 2014). It has to be taken into account, that all projects are R&D projects and not under the stricter requirements of real industry production. The listed costs are in the range of 1 000 – 3 000 €/kW_{el} installed electrolysis.

As long as natural gas is considerably cheaper as electricity, the conversion of power to gas can only be feasible, if the GHG advantage of the renewable product is honoured in any way (e.g. CO_2 certificates).

2.3.1 Demand and utilization of CO_2- *and* H_2-needed quantities and qualities and purpose of use, today and in future times

To estimate the demand of CO_2 and H_2 in order to produce methane (CH_4), the molecular formula according to the Sabatier process

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$$

is taken as basis, combined with the molecular masses of the elements as listed in Table 2-5.

Table 2-5: Molecular masses of Hydrogen, Oxygen and Carbon (rounded values)

Element	Symbol	Molecular mass [g/mol]
Hydrogen	H	1
Carbon	C	12
Oxygen	O	16

The formula expressed in molecular masses turns out to the mass balance as follows:

$$44\text{ g } CO_2 + 8\text{ g } H_2 \rightarrow 16\text{ g } CH_4 + 36\text{ g } H_2O$$

Normed to the demand of CO_2 per product the process needs 1 g CO_2 to produce 0.36 g CH_4 – according to 2.75 g CO_2 per 1 g CH_4. Calculated in volumes of gas, with the values of 1.848 kg/m^3 of CO_2 and 0.671 kg/m^3 of methane[14] this refers to 1 m^3 of CO_2 to produce 1 m^3 of methane. Normed to the different elements the mass and volume balances are shown in Table 2-6.

Table 2-6: Mass and volume balance of input (CO_2 and H_2) and output (CH_4 and H_2O) according to the Sabatier process, normed to the different elements

	g			
Input				
CO_2	1	5.5	2.75	1.22
H_2	0.18	1	0.5	0.22
Output				
CH_4	0.36	2	1	0.44
H_2O	0.82	4.5	2.25	1

	m^3			
Input				
CO_2	1	0.25	1	793
H_2	4.00	1	4	3 173
Output				
CH_4	1.00	0.25	1	793
H_2O	0.001	0.000	0.001	1

In chapter 2.2 general remarks about the needed quality and purity for the use of CO_2 and H_2 as feedstock for the chemical industry are given.

However, for P2G there are certain specifics to consider. First, the hydrogen shall not be produced by steam reforming, but via electrolysis of (renewable) electricity. The resulting hydrogen does not contain any relevant impurities and has a purity of 99.9% before gas treatment (Eichsleder and Klell 2012).

The Sabatier process for the reaction of CO_2 and H_2 to CH_4 and water runs under increased temperature and pressure in presence of a nickel catalyst. Alternatively, ruthenium on a

[14] www.linde-gas.at/de/services/gaseumrechner/index.html

substrate of aluminium oxides can be used[15]. So, the standards for safe and efficient operation of these catalysts have to be met.

Experience from (Zuberbühler et al. 2014) have shown, that CO_2 from various sources such as

- CO_2 from air capture
- CO_2 as by-product from bio methane
- CO_2 as by-product from bio ethanol
- CO_2 from the power sector (via CCS / CCU)
- CO_2 as by-product from the chemical industry

can be used without major problems. In contrast the requirements for product gas quality (methane, as to the requirements of DVGW[16]) have been met in all cases.

2.3.2 Needed power, needed quantities of gases

For the case of North Rhine-Westphalia, the scenarios of the "Climate Protection Plan NRW process"[17] give a good framework for a brief assessment of the amounts of power from renewable energy and resulting Power-to-Gas potentials.

It has to be stated, however, that the scenarios did not evaluate a downright surplus electricity potential, but generated a demand of hydrogen from different sectors (industry and transport) that could be met by renewable energy via electrolysis. This demand was calculated for different scenarios and iterated with the supply of energy in a bottom-up energy system simulation model. The data is appropriate to get an overview of the resulting demand of CO_2 and the amount of fuel, that could be met by the Power-to-Fuel process.

The calculation is based on a 70 % conversion efficiency of electrolyser in 2010, increasing up to 80 % in 2050. The bandwidth of scenarios is between scenario A ("conventional" climate protection approach, based on best available technologies, but no considerable innovations) and scenario B2/C2 (power sector based completely on renewable energy, considerable innovation through leap frogging).

The resulting amounts of CO_2 needed by 2050 (about 1.4 in scenario A to 14.2 Mt/yr in scenario B2/C2) and methane produced (about 0.5 to 5.15 Mt/yr) via Power-to-Gas according to the molecular formula (see chapter 2.3.1) are listed in Table 2-7 and Table 2-8. The numbers vary by a factor of ten, so a big bandwidth is given by these both scenarios. For scenario A, before 2030, no (renewable) electricity is used for the production of hydrogen.

[15] www.chemie.de/lexikon/Sabatier-Prozess.html
[16] www.dvgw.de/angebote-leistungen/regelwerk
[17] www.wupperinst.org/en/projects/details/wi/p/s/pd/396

Table 2-7: Balance of CO_2-needed and methane produced via Power-to-Gas process in NRW, based on the calculated amounts of hydrogen and electricity in scenario A

		2010	2020	2030	2040	2050
Electricity	PJ	0	0	1.28	19.82	37.78
	GWh	0	0	356	5 506	10 495
H_2	PJ	0	0	1	15	30
	GWh	0	0	267	4 267	8 396
	kt	0	0	8	128	252
	million Nm^3	0	0	95	1 524	2 998
CO_2	kt	0	0	44	705	1 387
	million Nm^3	0	0	24	381	750
CH_4	kt	0	0	16	256	504
	million Nm^3	0	0	24	382	751
H_2O	kt	0	0	36	577	1 135
	million m^3	0	0	0.0	0.6	1.1

Table 2-8: Balance of CO_2-needed and methane produced via Power-to-Gas process in NRW, based on the calculated amounts of hydrogen and electricity in scenario B2/C2

		2010	2020	2030	2040	2050
Electricity	PJ	0	1.38	18.69	176.72	385.76
	GWh	0	383	5 192	49 090	107 155
H_2	PJ	0	1	14	137	309
	GWh	0	278	3 894	38 045	85 724
	kt	0	8.3	117	1 142	2 574
	million Nm^3	0	99	1 390	13 584	30 609
CO_2	kt	0	46	643	6 284	14 159
	million Nm^3	0	25	348	3 399	7 660
CH_4	kt	0	17	234	2 285	5 149
	million Nm^3	0	25	348	3 405	7 671
H_2O	kt	0	38	526	5 141	11 584
	million m^3	0	0.0	0.5	5.1	11.6

The demand of electricity in scenario B2/C2 of 107 GWh by 2050 matches well to the results of a meta-analysis of climate protection scenarios. As portrayed in Figure 2-5, four of seven climate protection scenarios assume a power demand for hydrogen production of between 91 to 111 GWh.

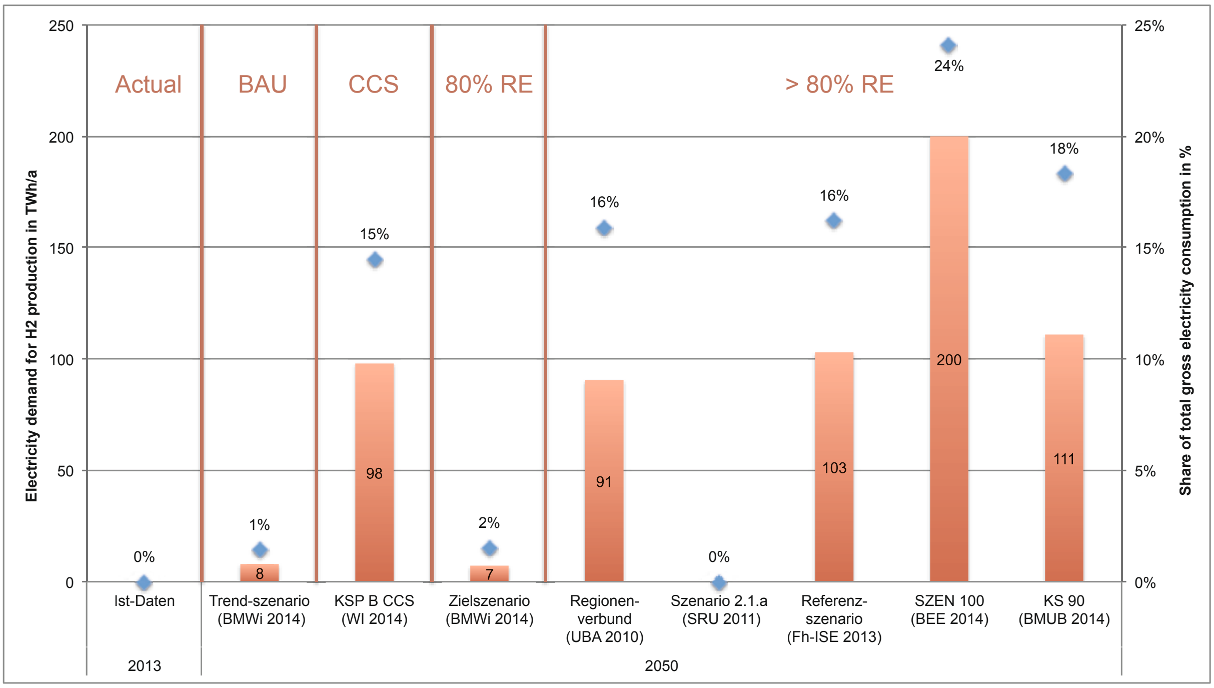


Figure 2-5: Electricity demand for H_2 production by 2050 according to BAU and different climate protection scenarios

BAU: Business As Usual / CCS: Carbon Capture and Storage / RE: Renewable Energy

In chapter 1.1 potential amounts of 42.4 Mt CO_2 emissions arising from the industrial sector (iron and steel industry, chemical industry, refineries, cement and lime industry, coking plants) and additional 46 Mt CO_2 from the power sector (CHP and waste-to-energy plants) were identified for a time horizon of about 2030. Table 2-9 shows the demand for electricity and the potential amount of produced H_2 and CH_4 for the theoretical case, that 100% of these CO_2 emissions were used as an input for Power-to-Gas processes. These amounts were calculated according to the molecular formula in chapter 2.3.1. In total 764.6 TWh of electricity would be needed to produce 535.2 TWh of hydrogen. NRW's total (fossil and renewable) net electricity production in 2012 was 122 TWh (IT.NRW 2014), so it would have to be extended by a factor of six and shifted to renewable production at the same time.

In respect to the amounts of CO_2 needed by 2030 (0.04 to 0.64 Mt/yr depending on scenario) the assumed remaining CO_2 emissions of 88.4 Mt per year in NRW would be sufficient to supply the Power-to-Gas path according to both scenarios. That means that CO_2 emissions in the mid term would not be the bottleneck, but the (renewable) electricity supply. On the long run even CO_2 emissions could run short for a methanation path, as the radical decarbonization scenario of UBA for Germany in 2050 (see chapter 3.3) demonstrates: A demand of 1.4 (scenario A) to 14.2 Mt/yr (scenario B2/C2) would have to be covered just for NRW, while only 19 Mt/a of CO_2 in total would remain for whole Germany by 2050.[18]

[18] In the Climate Protection Plan Scenarios, the bulk of H_2 produced is assumed to be used directly as a fuel or reducing agent in fuel cells or industry. So there is no "lack" of CO_2 in these scenarios.

Table 2-9: Amounts of electricity demand and H_2, CH_4 and water production according to the molecular formula for given amounts of CO_2 from industrial and power sector

		Industry	Power sector	Total
Electricity	PJ	1 320	1 432	2 753
	GWh	366 730	397 870	764 600
H_2	PJ	924	1 003	1 927
	GWh	256 713	278 509	535 222
	t	7 709 091	8 363 636	16 072 727
	Mio m^3	91 661	99 444	191 105
CO_2	t	42 400 000	46 000 000	88 400 000
	Mt	***42.4***	***46.0***	***88.4***
	Mio m^3	63 176	68 540	131 716
CH_4	t	15 418 182	16 727 273	32 145 455
	Mt	15.4	16.7	32.1
	Mio m^3	22 973	24 924	47 897
	GWh	229 042	248 489	477 530
H_2O	t	34 690 909	37 636 364	72 327 273
	Mio m^3	34.7	37.6	72.3

To get an idea, how big the potential of Power-to-Gas as a fuel for transport on basis of all remaining CO_2 emitters in the industrial and power sector in NRW would be, a comparison with the dynamic fuel market was done. Transport's fuel demand is taken from the same scenario as the data in Table 2-8, shown separately for the total fuel demand and the demand of gaseous fuel, e.g. CNG (compressed natural gas) and LPG (liquefied petroleum gas). These numbers develop conversely until 2030, as the overall demand of fuel decreases from 2010 to 2030 by 23 % (124 558 GWh in 2010 to 95 704 GWh in 2030) while the demand of gaseous fuels expands considerably. It almost doubles from 2 061 GWh in 2010 to 4 033 GWh in 2030. In the timeframe beyond 2030, both demands decrease to 75 722 GWh by 2050 for the overall transport fuel sector and 1 174 GWh for gaseous transport fuels.

Currently and until mid-term (2020), both the production of methane from Power-to-Gas as well as the demand of gaseous fuels are nearly marginal, compared to the overall demand of transport fuels (see Figure 2-6). As said before, the demand of gaseous fuels peaks in 2030 (according to the scenario B2/C2 considered here), when it could theoretically be met with methane from P2G. While production further increases, in the long-term (2050) even the overall fuel demand could be met with methane from P2G. But it has to be emphasised that these estimations are more theoretically than practically applicable, as they only base on the remaining CO_2 emissions. Other restrictions remain unregarded, such as a lack of renewable electricity or the risk, that the development of CNG as a fuel and the corresponding needed vehicles do not increase in a way that large amounts of gaseous fuels can be expected in the market. However, missing increase in CNG drive trains could be overcome to some extent by shifting to a Power-to-Liquid (PtL) path - with different H_2 and CO_2 ratios. To get the same amount of fuel less H_2 and more CO_2 would be needed.

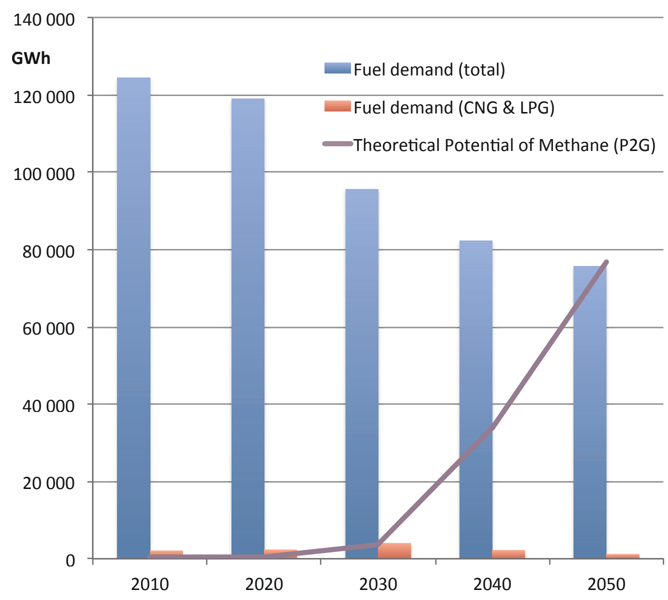


Figure 2-6: Fuel demand and theoretical amount of methane from Power-to-Gas as resulting from the scenario B2/C2 in the long-term until 2050

2.4 Current projects and activities (including demonstration projects)

The Federal Ministry of Education and Research in Germany (BMBF) launched a Funding Programme on "Technologies for Sustainability and Climate Protection - Chemical Processes and Use of CO_2" in 2009 (BMBF 2014). Some key innovations in the field of usage of CO_2 as feedstock could be achieved with this programme. The BMBF supports 33 consortium projects which bring together science and industry to drive development in the following areas (BMBF 2014):

- Migration or extension of the raw material base through utilization of CO_2 as a feedstock for the synthesis of basic chemicals
- Utilization of CO_2 for chemical energy storage
- Chemical activation of CO_2
- Innovation in CO_2 extraction, e.g. from power station gas emissions ("carbon capture")
- Reduction in greenhouse gas emissions in production through increased energy efficiency and the use of functional solvents[19].

Some examples from these areas are described in the following paragraphs. A list in the annex gives a broader overview over the different projects and the relevant actors.

The differentiation between different routes of CO_2 utlitization is not always useful, as the same product or intermediat can be used both as a building block for chemistry and fuels.

[19] Projects of "Energy-Efficient Processes and Avoidance of CO_2 Emissions" are not in the focus of this study, but are listed in (BMBF 2014 p. 21).

Methane is an example for that, methanol another: both can be used in the transport sector as well as in the chemcial industry, as shown in Figure 2-7.

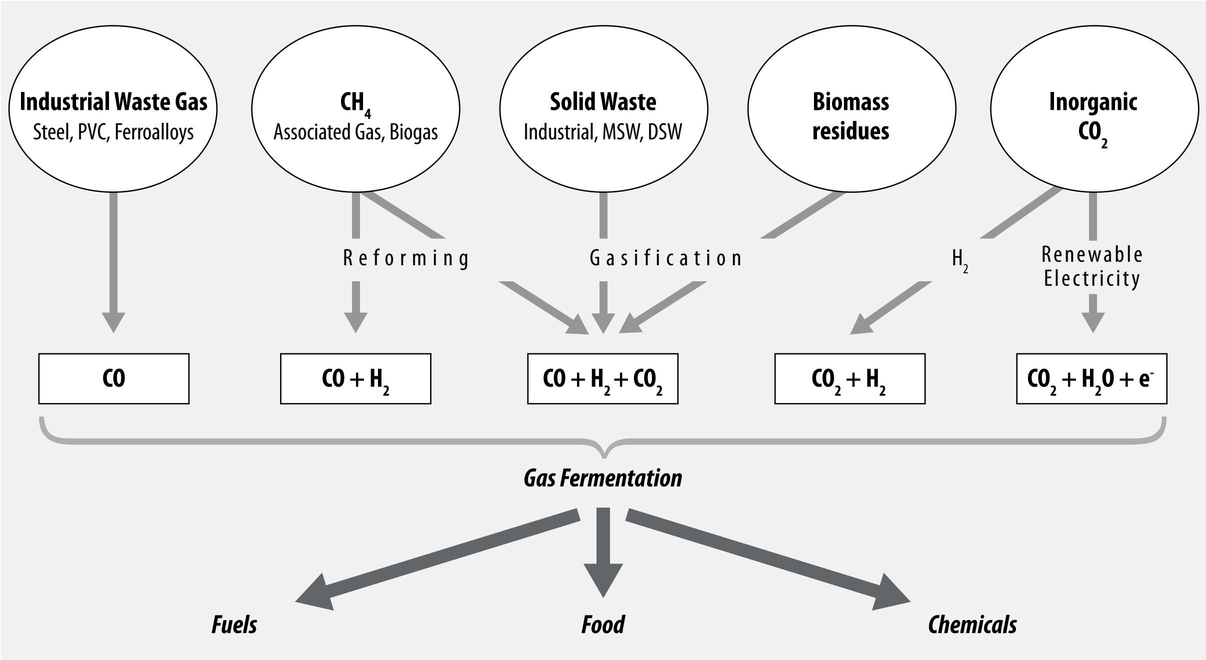


Figure 2-7: Different sources of CO_2 and diverse utilization options for products

Source: Own illustration after (Smith 2014)

2.4.1 CO_2 utilization in the chemical industry

A promising project in the field of CO_2-based polymers is the production of CO_2 containing polyether polyols developed by Bayer MaterialScience. Production of these CO_2-based polymer building blocks will start in 2016 in a commercial plant in Dormagen (Gürtler 2014). But there are also other research activities as listed in Table A 2. These projects are funded by the German Federal Ministry of Education and Research (BMBF) and target various base chemicals and potential key catalytic processes.

2.4.2 Biological CO_2 utilization

So far, the use of CO_2 by algae to produce hydrocarbons is hampered by two major limiting factors: the required lighting is usually artificial and based on the conventional power mix, and the resulting hydrocarbons have to be separated from the high water content of the algae biomass which requires significant energy input.

Worldwide there are only few examples for publicly sponsored industrial algae production in closed production plants. The biggest plant of the world can be found in Klötze, Germany: within the “Algomed project[20]”, micro-algae for the food industry are produced.

However, LanzaTech[21] as an international company is leading in microbial fermentation processes is currently operating a second pre-commercial facility and ready to open two commercial plants in 2015. With CO_2 taken from industrial plants, ethanol and hydrocarbon

[20] www.algomed.de/index.php

[21] www.lanzatech.com

fuels as well as platform chemicals are produced that are building blocks for products as rubber, plastics and fibres (Smith 2014).

2.4.3 CO_2 utilization projects on EU level

Projects in the field of CO_2-utilization are also being funded at the European level - besides the JTI initiative, dealing with hydrogen and avoidance of CO_2 emissions. Two projects are described as examples.

The goal of the project "CO_2 to Syngas[22]" is converting CO_2 to syngas with the use of solar light as energy source. In addition, water as abundant, non-toxic and sustainable resource will be used as electron and proton donor.

The RENOVACARB project[23] explores novel applications of renewable based molecules for the production of cyclic carbonates and polycarbonates by metal and organo-catalysed CO_2 fixation. The resulting molecules and materials will be characterized and evaluated for practical applications. RENOVACARB is designed to develop simple and feasible strategies for renewable resources exploitation by incorporation of CO_2 into added value molecules and materials, offering tangible alternatives to petroleum derived feedstock.

2.4.4 Research networks for CO_2 reuse

Among diverse research cooperation and collaborations, two networks shall be mentioned. The first one is "SCOT: Smart CO_2 Transformation" for the definition of an European research and innovation agenda (Armstrong 2014). Based in the UK at the center for carbon dioxide utilization, it focuses on the three routes CO_2 as chemical building blocks, for synthetic fuels and for mineralization. The networks aims at bridging the gap between academics and industrial implementation. So far, ten regions in five European countries (UK, the Netherlands, Germany, France and Wallonia) are involved; more are to follow.

The "CO2Chem - Carbon Dioxide Utilisation Network"[24] brings together partners from science, industry and policy, as well. The activities are focused on the utilisation of carbon dioxide as a single carbon chemical feedstock for the production of value added products by founding a cross-disciplinary research clusters. Over a 20-40 year time frame, strategies and technologies for the capture and reuse of CO_2 shall be identified and funding streams shall be implemented. So far, the CO2Chem network is mainly a collaboration of UK universities, the network intends to expand Europe wide.

2.4.5 Power-to-Gas and Power-to-Fuel demonstration projects

Furthermore within Germany and Europe there are several projects with demonstrator facilities converting power to gas. For Germany, an overview is provided by the German Energy Agency (Dena 2015)[25].

[22] www.highbeam.com/doc/1G1-390583375.html
[23] http://cordis.europa.eu/project/rcn/187691_en.html
[24] http://co2chem.co.uk
[25] www.powertogas.info

The first project listed there was started in 2009, a broader number followed in 2011 (five projects) and 2012 (eight projects). Altogether, twenty projects can be found on the list, covering various technologies around Power-to-Gas from methanation, injection to the grid as well as storage of hydrogen, production of electricity, fuel and even heat from hydrogen, hydrogen as feedstock for chemistry and the overall topic of waste heat utilization. The focus among the listed projects is on the methanation and on the injection of hydrogen into the grid and the use of hydrogen as fuel (see list and map of projects in Table A 3 and Figure A 9 in the annex). Table A 4 in the annex gives an overview of projects funded by the German BMBF that tackle CO_2 reuse for chemical storage and fuel synthesis.

2.4.6 Projects with H_2 transport

The existing pipeline network for hydrogen production in NRW is not necessarily a project but may be the backbone of a future hydrogen distribution system (see Figure 2-8).

Owing to the physical properties of hydrogen, distribution is possible in gaseous form via pipelines or by rail in tank wagons as well as using specialised ships or lorries. For other than transport via pipeline, cryogenic transport is an important alternative because the volume-related energy content of gaseous hydrogen is very low. This would result in enormous and costly vehicle mileage per unit of energy transported as compared to today's liquid fuels. In case of pipelines, dedicated hydrogen networks are an option. Moreover it is possible to transport hydrogen by pipeline mixed with natural gas applying membranes for separating the hydrogen close to its destination. The hydrogen content in the gas transported in existing pipelines may easily be 5 percent and in future it may even reach 20 percent. However, some applications typical for natural gas will have to be separated from such shares of hydrogen.

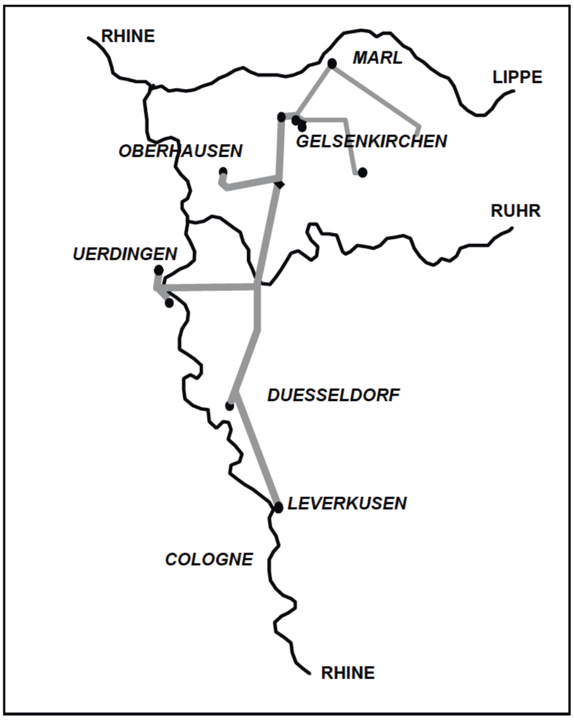


Figure 2-8: Hydrogen pipeline network in the Rhine-Ruhr area

Source: Based on Air Liquide (Fischedick and Pastowski 2010)

2.5 Milestone: Specification of promising applications for CO_2 and H_2 as a feedstock (current status and future perspectives)

From our today's point of view most promising future (chemical) non-captive uses of CO_2 as raw material are for the production of

a) polymers
b) platform chemicals like methanol, methane, formic acid,
   which can be used for subsequent synthesis of
   - chemical products, or
   - energy carriers.

When producing methane or methanol for use as energy carriers or energy storage media or as substitute for fossil based platform chemicals significant amounts of CO_2 would be required. The major bottleneck, however, might be the availability of renewable energy for the production of H_2, because a lot of hydrogen – or other forms of energy – is needed for the transformation of CO_2 to hydrocarbons. To stay environmentally friendly, the hydrogen has to be produced by means of renewable energies in a resource efficient manner. Currently, water electrolysis using regenerative energy like wind power is the dominant process route. Taking the current strong growth of renewable energy shares in the power sector into account, experts anticipate increasing amounts of surplus power from renewable sources in the future. This surplus energy could be an important driver for the development of CO_2 reuse technologies.

3 Sink-Source-Matching of carbon dioxide (CO_2) and hydrogen (H_2) in NRW

In this chapter the matching of CO_2 and H_2 sources and potential sinks is discussed. First, general remarks and prerequisites for the utilization of CO_2 are outlined (chapter 3.1). The quantities (masses or volumes) of available gases in NRW – today and in the future until 2030 – have been summed up in chapter 1. Based on these findings the potential utilization processes as sinks are discussed and three cases for the quantification of future CO_2 use are provided (chapter 3.2). In section 3.3, an excursus of an extreme scenario with a very ambitious mitigation pathway and complete utilization of the remaining CO_2 potential is given. This is followed by a qualitative discussion on the spatial distribution of sources and sinks in NRW (chapter 3.4). It is discussed which components for the production needed should be transported best (flue gas, purified CO_2, H_2, electricity, pre-products, products, …) and what the limits for reasonable paths of utilization are. For example it might be more efficient in some cases to directly use the energy needed for conversion processes. It is concluded where potential production sites might be erected in North-Rhine Westphalia[26]. In the end, a longer time horizon until 2050 is taken into account and milestones for selected value chains are presented (chapter 3.5).

3.1 General remarks and prerequisites for utilization of CO_2 and H_2

CO_2 in flue gases from power plants and industry has a very low energetic level (Sakakura et al. 2007). To use CO_2 in a sustainable manner, it has to be activated with additional non-fossil energy or by photocatalytical ways like biological or artificial photo synthesis (Ausfelder and Bazzanella 2008). The use of catalysts is crucial to accelerate the reaction and to diminish the expense for the activation energy. This catalytic conversion is a huge research field whose success would help to foster the utilization of CO_2.

The chemical composition of the flue gas is important with regard to purity. In general it can be stated that high purity is needed to have the highest spectrum of possible forms of utilization, which is basically a question of costs. Heavy metals, halogens, sulphur, CO or traces of polymer might work as catalyst poisons which would inhibit chemical reactions. The highest concentration of CO_2 in flue gases are from steam reformers in chemical industry and refineries (up to 100%), especially in the production of ammonia and ethylene oxide (compare Table 1-1). The occurring CO_2 in ammonia production is partly used for urea production.

So far, most ammonia is based on fossil hydrogen from natural gas or oil. In the future, it could be synthesized from renewable hydrogen instead. Currently, 24 megaton (Mt) ammonia is produced per year in Germany, hence there is a considerable potential to use renewable H_2 for this application. Other chemical use for renewable H_2 could be in hydrogenation or as reduction agent in metallurgical processes.

Another suitable source is CO_2 from biogas-to-biomethane treatment plants on a renewable basis, with high concentration (40 to 44 % in the raw biogas), but very small volume (41 700

[26] To further improve these findings, in a next step a detailed geographic analysis of the available and/or the future expectable infrastructure at these sites like pipelines for natural gas, CO_2, CO, H_2 or electricity grid with high level of voltage should be conducted.

t/a in NRW). In these plants CO_2 is a component in the biogas that must be removed for the purpose of product quality and that is currently vented to the atmosphere. It is easier and cheaper to extract such pure CO_2 rather than flue gases from conventional power plants which include only 3 % (gas-fired) to 14 % (coal-fired) of CO_2 and up to 70 to 80% of nitrogen (see Table 1-1). Though flue gases from (future) oxyfuel power-plants contain a considerable higher fraction of CO_2 (up to 30%). Additionally, research commences to capture CO_2 from ambient air (Keith 2009; Lackner 2009). The advantage of this method is that it can be applied wherever the CO_2 is needed. The problem is the low concentration of CO_2 in the air (0.04%) and hence higher energy and capital costs involved in comparison to capture from flue gases (see Figure 3-2 in chapter 3.3).

The duration of CO_2-fixation in a product is dependent on the application. If CO_2 is used to produce methanol or urea for example, the fixed CO_2 is released back to the atmosphere by burning the methanol or using the fertilizer. In polymers, the fixation is considerably longer (Kuckshinrichs et al. 2010). A positive aspect from utilization of waste-gas CO_2 is the substitution of natural occurring CO_2 sources. Most forms of utilizing CO_2 is linked to the production of hydrogen (H_2) first. H_2 production can be achieved through electrolysis of water. Thus to apply large scale CO_2 neutral products, renewable and cost-efficient H_2 infrastructure is needed (Ausfelder and Bazzanella 2008). Such material utilization should be preferred to energetic utilization of input gases. For instance, coke oven and converter gas from steel-industry could be partly used as input for chemical industry as it is intended in the CleanTechNRW lighthouse project *CO2nvert*. A demo plant is designed to increase the energy efficiency of the process through industrial symbiosis, combined with the production of the intermediate products methane (for energetic use) and benzene (for chemical use) (CleanTechNRW o.J. p. 41 f.).

3.2 Quantitative estimation of future CO_2 and H_2 reuse potential in NRW

In this section, a quantitative estimate of future reuse potential of CO_2 and H_2 in NRW is provided. Criteria which would influence the harvest of this potential are described in section 3.4. These are cost issues, infrastructure and compatibility with existing systems or technological lock-in effects.

The global industrial use of H_2 amounts to 40 to 50 Mt/a with about half of it for ammonia production. The global utilization of CO_2 in industrial processes is very low with only 0.5% of annual energy related CO_2 emissions (115 - 200 Mt CO_2/a). 60% of CO_2 is used for urea production. Besides urea, CO_2 is physically applied in larger quantities for enhanced oil production in North America. There is potential to substitute natural CO_2 sources with industrially captured CO_2. From the global perspective, it is assumed for the future that 1 to 5% of emitted CO_2 could be integrated in product manufacturing (IPCC 2005), underlined by IPCC (2014). Thus CCU is no option to contribute to large scale global emission reduction, but it can have an attractive position in carbon management in specific regions.

For NRW, prospects of utilization of CO_2 is rather focused on material use than on physical application, but it is very difficult to estimate the available potential for the future. Hence, the NRW potential is approached with the following three cases:

Case A: Based on the global assumption of 1 to 5% of current emissions,

Case B: Based on the estimated available CO_2 emissions in NRW in the midterm (2030),

Case C: Based on the volume of products where CO_2 could be integrated, exemplary based on current production of methanol, polymers and demand for methane.

It is assumed that each potential will be tapped completely by the year 2050. A compilation of all three cases can be found in Table 3-3 and Figure 3-1.

3.2.1 Case A: Global Assumption

If the global assumption of the potential use of CO_2 is applied to NRW, only **2.9** (**case A_{min}**) to **14.3 Mt CO_2** (**case A_{max}**) might be used until 2050, based on the total emissions of 287 Mt CO_2 in 2012. This would be about 3.2% to 15.5% of the future remaining emissions from industrial and CHP/waste-to-energy plants of 88.4 Mt CO_2/a, as identified in chapter 1.1 for the year 2030. The application of this global assumption can only provide a first rough estimate for the purpose of orientation. It is based on the current emissions which will be varied in the future. Additionally, it should be noted that this approach likely overrates the potentials because today's NRW emissions are mainly derived from lignite-based power plants, which lead to disproportionately high per capita emissions compared with the national or global level.

3.2.2 Case B: CO_2 emissions from industry, waste incineration and CHP in NRW

Case B consists of projections of CO_2 availability in NRW. As deduced in section 1.1 in detail and summed up in the milestone of chapter 1.4, the future availability of CO_2 from industry, waste incineration and CHP plants amounts to **88.4 Mt CO_2/a (case B)**. In this case, this estimated potential is supposed to be utilized completely by 2050 in NRW.

3.2.3 Case C: Potential utilization processes for CO_2 and H_2 in NRW

This case relies on potential utilization processes in NRW. Most important are three processes for the utilization of CO_2 and H_2 in the future: The synthesis of *methanol*, the synthesis of *methane* and the production of *polymer*. Both methanol and methane can be used directly or for subsequent synthesis of chemical products or energy carriers.

In chapter 2.3, the production of methanol (Power-to-Fuel) and methane (Power-to-Gas) is described in detail. NRW has a production capacity for **methanol** synthesis of 700 kiloton per year (kt/a). To produce such an amount, **960 kt CO_2** and 65 kt H_2 are needed with an energy input of ca. 2.2 TWh H_2 (or 2.7 TWh electricity if produced via electrolysis) (**case $C_{methanol}$**). For that process, special catalysts are needed if CO_2 is used as a feedstock directly instead of CO[27]. Synthetic **methane** can be produced via the Sabatier process with input of CO (CO_2) and H_2. It might be injected into the existing gas pipeline network and can be used as transport fuel, for heating, as chemical building blocks or for power production[28]. If theoretically the entire German consumption of natural gas with 956 TWh by 2013 would be substituted by synthetic methane, 64 Mt of methane needs to be produced. For that amount,

[27] Otherwise energy intensive reversed water gas shift reaction processes are needed to get CO out of CO_2.

[28] In the case of re-electrification the total conversion efficiency of power to gas and back to power is assumed to be about 28% (see Table 2-4 on page 34).

176 Mt CO_2, 32 Mt H_2 and 5 477 PJ electricity would be needed (**case $C_{methane}$**). To put this into perspective, the entire German primary energy demand in 2013 amounts to 14 000 PJ, hence this conversion path can be stated as very optimistic. Production of methane or methanol would be only cost effective at very low electricity prices, i.e. based on surplus electricity.

In contrast to production of ammonia, urea or methane/methanol, the *chemical fixation of CO_2 and H_2 in plastics (i.e. **polymers**)* is for the longer term. In chemical industry there is a large range of polymer synthesis and co-polymerization, e.g. to fabricate plastics, as described by (Centi et al. 2007; Nalawade et al. 2006). Some examples are polypropylene carbonate (PPC), polyethylene carbonate (PEC) or bio-based plastics like polylactic acid (PLA) or polyhydroxyalkanoates (PHA). One example from Bayer Material sciences is the project “dream reaction” where polyurethane blocks from CO_2 polyols are used. The used CO_2 prevails from a lignite power plant, and research is focused especially on improving catalysis as key technology.

If the polymer production in Germany for the entire *domestic* demand was shifted towards CO_2 utilization, 4 Mt of fossil carbon would be required. If that amount was to be supplied completely on the basis of captured CO_2, 15 Mt CO_2 would be required beside 2 Mt H_2 and 83 TWh electricity (see chapter 2.2.1). The capacity of steam crackers for ethylene in NRW accounts for roughly 65% of the German capacity (Fraunhofer ISI et al. 2011). Assuming that this proportion is similar for polymer production in NRW, it is estimated that **10 Mt CO_2** and 1.3 Mt H_2 could be used (**case $C_{polymer}$**).

Combining the three potential forms of utilization within **case C** (ca. 1 Mt CO_2 for methanol, 176 Mt CO_2 for methane synthesis and 10 Mt for polymer production), the theoretical CO_2 utilization potential amounts to **187 Mt CO_2**. The equivalent quantum of H_2 use amounts to 33.4 Mt (65 kt H_2 for methanol, 32 Mt for methane and 1.3 Mt for polymers).

At the current availability of captured CO_2 and produced H_2, only small scale demo or pilot plants could be designed. In order to achieve a higher combined use of H_2 and CO_2, capture technologies should be improved to purify the CO_2 excess stream. However, more important is the need for renewable and cost-efficient H_2 in large amounts. The question where electrolysis capacities should be situated is touched on in chapter 3.4.

3.2.4 Comparison of cases

Summing up the three cases for future use of CO_2 and H_2 in NRW explained above, a large corridor of potential utilization prospect is drawn (Figure 3-1). Most curves are in the range of up to 10 Mt CO_2 by 2030 and up to 15 Mt CO_2 use by 2050. Only the use of all available CO_2 in 2050 (case B) and the synthetic production of entire methane demand in Germany (case $C_{methane}$) exceed that range.

In addition to the three mentioned cases, the estimation of (UBA 2014) is included in Figure 3-1 (compare excursus in section 3.3). The **UBA scenario** provides CO_2 emissions from industry (mainly lime and cement clinker) and biogas of 19 Mt for Germany as whole by 2050. Based on an estimated share of 20 to 25% of emissions, this would lead to future emissions in NRW of **4 to 5 Mt CO_2/a**. All estimated curves in Figure 3-1 are linearly interpolated from 2015 until 2050.

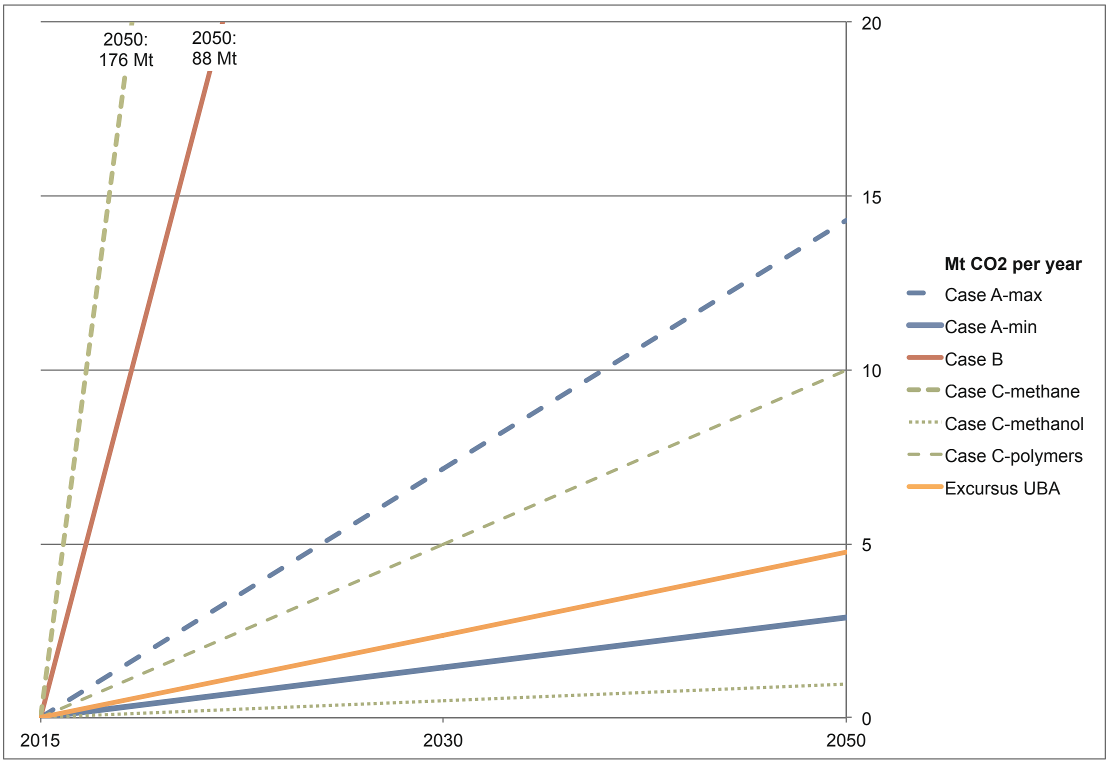


Figure 3-1: Future theoretical potential of CO_2 utilization in NRW based on different cases

- A: **Global assumption**
  (case A-min: 1% of total emissions; case A-max: 5% of total emissions)
- B: **NRW emission approach**
  (use of all future remaining CO_2 emissions from industry, waste incineration and CHP in NRW)
- C: **Volume of products approach**
  (current demand for natural gas, production volumes of methanol and polymers)
- D: **Excursus UBA 2050**
  (UBA scenario of a carbon-neutral energy supply system by 2050)

3.3 Excursus: Principal match of CO_2 emission reduction and CO_2 reuse

The key question for the prospects and limitations of CO_2-Reuse-options is: how can they fit together with the ambitious overall reduction goal for CO_2 emissions (80 % to 95 % for Germany until 2050 compared to 1990)? Or to ask it more bluntly: If the CO_2 emissions are to be as less as possible as soon as possible, what sources and chances at all will remain for the reuse of CO_2 and what are the corresponding requirements and implications thereof? These questions motivate the following short analysis exemplary done on the basis of the recently published study “Germany 2050 - A Greenhouse Gas-Neutral Country“ by the German Environment Agency (UBA 2015)[29].

This study aims to show that it is technically feasible to bring the total greenhouse gas emissions of Germany nearly down towards zero in the year 2050. In this respect the study describes a kind of extreme scenario[30]. The whole energetic as well as the non-energetic

29 Title of the original German version from April 2014: “Treibhausgasneutrales Deutschland 2050” (UBA 2014)

30 For a better understanding of the challenge at all, the current status quo may be helpful: Carbon rich educts (incl. CO_2) are in use today in remarkable amounts as a feedstock for some industrial processes (see chapter 2). This leads to significant non energetic CO_2 equivalent emissions, which are in the order of about 60 - 70 Mt/a or about 7 % of the total GHG emissions in Germany (BMWi 2013), (UBA 2015). The educts mainly base on fossil resources. In addition about 2/3 of the industrial energy demand is based on fossil fuels like oil and natural gas. By its combustion the German industry contributes to the total energetic CO_2 emis-

industrial demand would then be covered on the basis of renewable energies. This would be supported by energy efficiency / saving measures and the production of renewable hydrogen, renewable methane and renewable fuels by renewable electricity. The two last options need CO_2 as educt from the few remaining CO_2 sources, which are suited for a CO_2 reuse (see Table 3-1).[31] To this category of CO_2 sources only belong the production of biogas out of organic waste and residual materials (27 %) and the process related emissions especially from the cement and lime industry (73 %) with together around 19 Mt/a of CO_2 by 2050. This amount could be theoretically reused for a production of about 419 TWh of synthetic Methane if the CO_2 was completely captured without any CO_2 losses. However, one has to keep in mind that this value is rather an upper and / or optimistic estimation because neither losses, nor technical, infrastructural or economical constraints have been considered for the calculation.

Table 3-1: Annually CO_2 emissions by sources in the year 2050, theoretically suited for CO_2 reuse in Germany (according to the UBA scenario)

CO_2-source	**Amounts of CO_2 in Mt/a**	**CH_4 production potential in TWh/a**
Biogas*	5.28	116
Industry**	13.78	303
Sum	**19.06**	**419**

* from biogenic waste and residues with shares of about 40 % CO_2 and 60 % Methane (CH_4)
** mainly from cement- and lime industry

Source: Data from (UBA 2015) plus own calculations

At first sight this seems to be a quite high amount of “renewable” methane, which can be supplied (among others like biomethane) by CO_2 reuse even in that ambitious case of a system with nearly zero CO_2 emissions. However, the comparison with the remaining demand for methane as fuel and feedstock by (mainly) the industry sector shows that there would be still missing an amount of CH_4 in the order of around 60 TWh within this ambitious future energy system (see Table 3-2). This deficit would raise to about 105 TWh of methane in an UBA scenario variant, where additionally the demand by the residential sector is considered (UBA 2015)[32].

Table 3-2: Demand for renewable methane as fuel and feedstock in a GHG-neutral Germany in 2050

CH_4 Demand in Industry …	**In TWh**
… as fuel	199
… as feedstock	282
Sum Demand	**481**
CH_4 Supply from CO_2 Reuse	419
Balance	**-62**

sions in the order of around 170 Mt/a. Thus the big challenge is, to bring the industrial CO_2 emissions nearly down to zero and / or to substitute (recycle) the fossil based CO_2 by renewable, “green” CO_2.

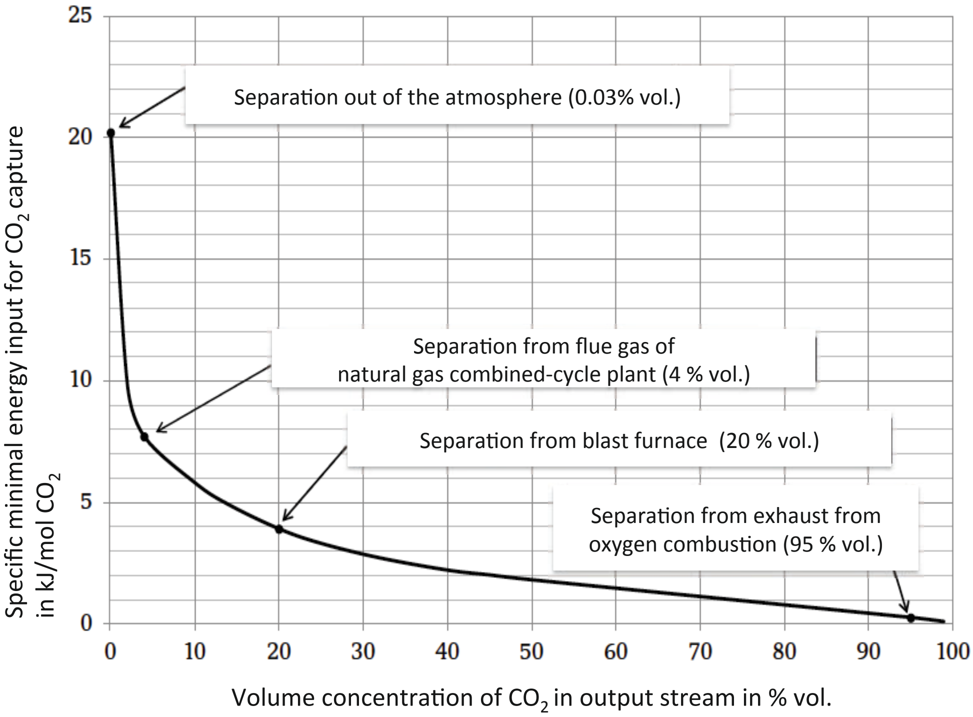
31 The other still remaining and remarkable CO_2 sources at the transport and residential sector and at back-up power plants will not be (directly) suited for a CO_2 reuse, because they are too diffuse and / or too costly. Thus these sectors have to be decarbonized by usage of renewable energies and fuels in the considered study.

32 Variant V3 (UBA 2015 p. 85)

Source: (UBA 2015)

Thus this deficit of "renewable" methane has to be compensated by imports from other countries and / or by the capture of CO_2 out of the air. However, from a present-day perspective, the latter option is not really sustainable because it is very energy intensive to capture CO_2 from gas streams with low CO_2 concentration (see Figure 3-2). This would further raise the already very high electricity demand for the production of renewable methane. Thus the renewable electricity, which would still be needed for processes in the industry sector in 2050, is round about 160 TWh plus a demand of about 200 TWh of renewable methane. Together with the electricity demand for the preproduction of hydrogen, the total industrial related energy demand sums up to more than 1 000 TWh (net value) of electricity which has to be generated by renewable energies for the production of fuels for stationary applications. This demand raises by a factor of three in order to fulfil also the demand for fuels[33] in the transport sector.

Figure 3-2: Minimal energy demand for CO_2 capture in dependence on the CO_2 concentration



Source: (UBA 2014 p. 64), own translation

<u>Conclusions:</u>

Following the above mentioned UBA scenario for 2050 an absolute closed loop of CO_2 is not possible.

Even if all suited CO_2 emission sources would be captured, there always will remain a remarkable need for external "green" (non-fossil) CO_2. As the same rule will apply for other countries, in the end a certain share of the needed CO_2 has to be captured from the air with high expense with respect to energy, resources and costs.

33 Only liquid fuels assumed, supplied by Fischer-Tropsch process using RE-Electricity, no gaseous fuels.

CO_2 capture and reuse at bigger[34] industrial and biogas plants is a requirement in a future world of climate protection. However at the industry on beforehand one rather has to substitute the fossil fuel and feedstock supply because otherwise it will be no “green” CO_2 (lock-in effect at the fossil system).

The potentials and options will be in reality much less than given in the study due to technical, economic and other reasons.

3.4 Qualitative discussion of potential locations and transportation options

In Figure 3-1 the large variation of potential CO_2 use in NRW is demonstrated. In order to achieve one or another of these future utilization pathways, different criteria are involved such as costs, infrastructure, system compatibility or technological lock-in effects. These will be outlined in the following qualitative description in more detail.

No matter which amount of future CO_2 production will be utilized, it is still an open question which material should be transported: electricity, H_2, CO_2, pre-products or final products. CO_2 is available in much bigger volumes than H_2 although the capture and purification issues need to be solved. However, as analyzed above, cost-efficient electrolysis based on renewable excess electricity is key to most utilization processes (compare chapter 2.5). Electrolysis to produce H_2 is principally - at small scale - a mature technology with high efficiencies. But so far the electrolysis process is very cost-intensive especially if the electrolyzers can not be operated in baseload mode. However, the H_2 has to be created renewably to have climate importance. If e.g. conventional electricity was used to produce H_2 for 1 ton of methanol synthesis, about 5.7 t CO_2 would be emitted whereas only 1.9 t CO_2 would be sequestered in the product (Kuckshinrichs et al. 2010). There would be lock-in effects, if constant H_2 stream was needed for synthesis processes as described above. If at some periods fluctuating renewable electricity is not available, fossil power might jump in to produce the necessary electricity for electrolysis.

The spatial distribution or concentration of new electrolyzers is important. Central questions are whether the intended site is connected to natural gas pipeline or high-voltage grid, which are prerequisites for the construction of electrolyzers. A welcoming opportunity is a strong inter-sectoral integration with electricity, heat, transport and industry production. There are three major options to lay different spatial foci for the infrastructure of CO_2 utilization:

a) Close to wind power plants in Northern Germany, possibly with adjacent Power-to-Gas / methanation plant. The produced H_2 (up to a certain concentration) or methane could be transported through the existing gas pipeline network. About 5% of H_2 might be mixed within the natural gas, but it is not easy to extract the hydrogen from methane again, if a pure utilization of H_2 is wished. It might be even more efficient to build a regional grid for H_2.

b) Close to current and potential utilization sites of H_2, possibly close to chemical industry. There needs to be a high-voltage grid connection to transport excess electricity to these sites.

[34] Due to economic reasons CO_2 capture does make sense only as of a certain size of plant or a certain amount of yearly emission CO_2 emission.

c) Regional coupling of photovoltaic and electrolysis at the distribution network of communities. Storage of electricity might help to build up such a system.

Additionally, CO_2, CO and H_2 from other processes like flue gases from blast furnaces in steel industry or biogas/biomethane plants could be used and should be linked to the potential production facilities.

Depending on the three assessed cases (compare section 3.2), the utilization potential in NRW is in the range between 3 to 14 Mt (case A), 88 Mt (case B, where all future available CO_2 from industry and CHP power plants is used) and up to 187 Mt CO_2 (case C). Depending on the development and amount of CO_2 used in the future, it is questionable, whether a CO_2 pipeline would be constructed or if transport will be realized by ship or train. For the pilot phase, truck transport might be an option too. Thinking about CO_2 logistics, it might lead to a regional pipeline as demonstrated in the Netherlands from the refinery in Pernis to greenhouse sites with a capacity of 105 t CO_2 per hour. If such a CO_2 pipeline network is considered, the integration of currently available high volumes of CO_2 emissions from fossil-based power plants might facilitate the construction although it is assumed that these sources will have to diminish in the future. If these sources were substituted in the mid to long run by industrial CO_2, an extension or new pipeline infrastructure would be needed, especially if high volumes of CO_2 will be used. Such industrial sources have higher CO_2 purities and might last longer at the existing sites and could as such be considered as nucleus for the CO_2 infrastructure. Due to estimated production shifts and yet unknown issues, the CO_2 availability will fluctuate in the future. This makes a possible CO_2 infrastructure with a lot of potential sources and sinks even more feasible as it can cope with this fluctuation.

Hence, it seems to be most efficient to utilize CO_2 close to the sites with CO_2 sources. At most sites, a connection to the high-voltage grid is available and electrolysis might be done on-site to produce H_2. But for this case it has to be verified if the power grid has sufficient capacity to transfer excess of renewable electricity from the renewable "hot spots" in the north and east of Germany. For reasons of cost efficiency, the grid will not be extended to transport electricity *at all peaks* of supply so that a part of the power feed-in must be curtailed. If the above-mentioned CO_2 potential will be tapped, up to 9 Mt renewable produced H_2 will be needed in NRW. This would lead to a consumption of roughly 300 TWh electricity, which is half of the current German electricity consumption (600 TWh in 2013).

Another option would be to transport hydrogen via local, regional or even interregional hydrogen pipelines to the CO_2 utilization sites. Products like methane could be transported to other sites. Table 3-3 gives an overview of potential products and their production sites. Production sites of synthesized materials like polymers or methanol are supposed to be linked to existing chemical industry sites. Comparing the potential use of up to 187 Mt CO_2 with the available emissions along the River Rhine of about 40 Mt (compare Table 1-1), one pipeline along the river would not be enough and additional emissions from the power-sector would be needed. Nevertheless, even the assumption of using 40 Mt CO_2 seems very optimistic from the current perspective. But if in contrast to that the CO_2 emissions from the UBA long-term scenario for 2050 - as discussed in the excursus of chapter 3.3 - are taken into account,

- the remaining amounts of CO_2 are considerably lower with only 19 Mt for entire Germany (and hence only 20 to 25% of that for NRW).

- almost only emissions from the cement and lime industry are available which are scattered across the eastern part of the federal state (see Figure 1-2 in chapter 1.1).

Table 3-3: Overview of potential future products made from CO_2 and H_2 and their potential production sites

Products	Polymers	Methane / methanol and other synthetic fuels
Where to produce?	Chemical industry (substitution of existing processes)	Not specified (advantageous close to CO_2 sources, natural gas grid, gas storage sites or gas-fired plants. For further synthesis, close to chemical industry)
Input H_2	Renewably produced H_2, i.e. electrolyzer has to be erected at site and access to high voltage grid is needed (input of renewable energy).	
Input CO_2	Various CO_2 sources along the river Rhine (existing chemical industry is situated mainly along that river). Only chemical park Marl is in the Ruhr area, where available CO_2 sources exist as well.	Production sites can be chosen close to available (now and in the future) CO_2 sources. If large-scale methanol synthesis is intended, CO_2 from current power plants (or from neighboring countries) would be needed.
Quality of CO_2	For all processes, high purity CO_2 streams are very favorable. Hence first the sources with high purity are chosen. In the long run, capture costs will increase to provide purest CO_2.	
Case A) **CO_2 potential of 1 to 5% of todays total emissions**	3 to 14 Mt CO_2	
Case B) **Available CO_2 in 2030 (industrial, waste energy plants + CHP)**	88 Mt CO_2	
Case C) **Current production**	4 Mt plastic/a	0.7 Mt methanol/a
Future production potential	One-third of production is for domestic use. This is substituted with CO_2 use: 1.3 Mt plastic/a	Entire methanol of 0.7 Mt is produced renewably with excess CO_2 Entire natural gas demand (956 TWh by 2013) is synthesized (64 Mt CH_4).
Potential use of CO_2	10 Mt CO_2	1 Mt CO_2 for methanol 176 Mt CO_2 for methane
Potential use of H_2	1.3 Mt H_2	0.065 Mt H_2 for methanol, 32 Mt H_2 for methane
Excursus UBA 2050 **Available CO_2 in a nearly decarbonized Germany**	19 Mt CO_2 (for Germany) with roughly 20 to 25% from NRW: 4 to 5 Mt CO_2	

3.5 Milestone: Specification of selected value chains (future perspectives)

The theoretical potential for CO_2 use largely varies among the different presented cases (compare Figure 3-1). In the long run until 2050, the decarbonization of the energy system is supposed to intensify and industry production will be less emission-intensive. If on the one hand, a very ambitious pathway is followed, e.g. as presented by (UBA 2015), CO_2 emissions from iron and steel or chemical industry will almost be completely reduced (compare chapter 3.3). In this case, in NRW only 4 to 5 Mt CO_2 would remain in 2050. If on the other hand, the decarbonization of industry will not develop in such an ambitious way, it could be an interesting business case for industrial emitters to provide large quantities of CO_2 for utilization. The production of H_2 and the transformation of CO_2 into a future feedstock will change existing value chains.

Input:

- First and most important, renewable and economically available H_2 is needed for most value chains with regard to CO_2 utilization. Hence, a reliable electrolyser infrastructure is needed. Necessary electrolysers are supposed to be prevailingly constructed close to existing industrial sites and (excess) renewable electricity is transported to these sites.
- Bio-methane plants could work as nucleus for (small) pilot plants as the captured CO_2 is very pure and the capture process must be done anyway. Additionally, some processes of chemical industry and refineries provide very pure CO_2 streams.
- CO_2 captured from other industries such as via amine scrubbing or oxy-fuel technology from cement production or Top Gas Recycling in iron and steel industry could come into play if more CO_2 is needed. But it is more costly to produce purified CO_2 from these sources.
- If one day CO_2 from industrial sources or power plants disappeares, there will always be the possibility of air capturing. But if R&D will not succeed in significantly lowering the very high specific energy needs (and costs) for this technology of capture, it will rather remain a theoretical option.

Output:

Based on input from available CO_2 and H_2 in NRW, mainly four utilization paths are in the scope of analysis:

1. Large H_2 sources would lead to new value chains based on this energy carrier. Direct use of hydrogen for process heating, as fuel or as feedstock might be developed.
2. From CO_2 and H_2 as input parameters, methanol can be synthesized. It can be used as fuel or as feedstock in chemical industry.
3. Additionally, methane might be synthesized (Power-to-Gas) for all kinds of purposes. The advantage is the existing infrastructure for natural gas.
4. A more visionary, but the only utilization path for longer term CO_2 fixation, is the polymerization of CO_2 and H_2 into different kinds of plastics.

It has to be discussed whether the wished industrial symbiosis and integration processes between industries to use CO_2 could provoke less ambitions to mitigate emissions. If the industry shifted towards large use of CO_2 and renewable H_2, there might also be CO_2 logistics introduced which should be accessible beyond 2030 potentially even with neighboring countries. This could lead to a lock-in effect preventing industry to introduce other low-carbon technologies which omit CO_2 completely.

4 Methodological background for a systematic multi-criteria analysis (MCA) of value chains for CO_2 reuse

In order to contribute to a sustainable development, the prospective value chains for the utilisation of CO_2 have to be evaluated not only with regard to their potential technical performance but also in terms of their potential ecological, economic and social consequences. This chapter describes the Multi-Criteria Analysis (MCA) as an analytical framework which helps to integrate quantitative and qualitative data, consider all dimensions of sustainability simultaneously, compare them in a standardised approach and allows stakeholder participation. Since a main part of an MCA is determining a criteria set against which the alternative options are assessed, potential assessment criteria will be identified. A selection of these criteria will described in detail, specifically regarding their application on the value chains of this study. They could also be used in a more simplified comparative analysis, independently from an MCA. Since this study has a more explorative character, the assessment itself will be conducted at a later time, so that results will not be presented in this chapter.

4.1 Approaches for integrated sustainability assessment of technologies and processes

4.1.1 Overview on preconditions and requirements that need to be respected in approaches to evaluate value chains

Efficient resource use and technology development play key roles in transition processes towards a sustainable development of the economy. In order to fully exploit the potential of new technologies, the considered value chains for the utilisation of CO_2 have to be comprehensively evaluated, analysing not only their technical performance but also their ecological, economic and social consequences. The awareness and knowledge of these effects are a precondition to promote decisions towards sustainable development (Geibler and Rohn 2009).

According to Ness et al. (2007, p. 499) the purpose of sustainability assessments is *“to provide decision-makers with an evaluation of global to local integrated nature-society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society sustainable*”. Sustainability assessment methods like an integrated assessment provide theoretical well-founded instruments to address these tasks and to operationalize the normative approach of sustainable development. Assessing the sustainability potential of industrial value chains is a complex task as quantitative and qualitative as well as internal and external factors need to be systematically considered and assessed. In the present case, where value chains have to be evaluated prior their realisation to support planning and decision-making processes, additionally a number of assumptions and estimations about the future implementation of the considered technologies must be considered.

Over the last two decades various sets of guiding principles have been developed to make the concept of sustainable development applicable. Well-known are for example the Bellagio Principles and their further development, the Bellagio Sustainability Assessment and Measurement Principles, also called as BellagioSTAMP (Pintér et al. 2012, p. 20). Also, the European Union has adopted key objectives and guiding principles in 2006, offering a basis for a renewed strategy to address the challenges of a sustainable development in Europe and the world. The four key EU objectives are (1) environmental protection, (2) social equity and cohesion, (3) economic prosperity and (4) meeting international responsibilities. The 10 policy guiding principles include: promotion and protection of fundamental rights, solidarity within and between generations, open and democratic society, involvement of citizens, involvement of business and social partners, policy coherence and governance, policy integration, use best available knowledge, precautionary principle and make polluters pay (EU Commission 2005). Currently under discussion is a set of Sustainable Development Goals (SDG), that are developed by an Open Working Group of the United Nations General Assembly (UN General Assembly 2015). The SDG shall refine and extend the former Millennium Development Goals (MDG). They will explicitly applicable also for industrial countries and might therefore be of interest for the future assessment of value chains for the utilisation of CO_2.

Although these principles are important and need to be especially respected in EU projects, they have not been translated into an instrument for technology assessments, but refer to the general challenges of a sustainable development in Europe and worldwide (EU Commission 2007). Accordingly, it is not possible to directly transfer these principles into sustainability requirements for value chains for the utilisation of CO_2. In order to evaluate these technology pathways with regards to their sustainability, it is necessary to determine which sustainable development principles are applicable and relevant for technology assessments (Grunwald und Rösch 2011, p. 3).

Grunwald (2012, p. 51) has specified some principles that are applicable in a technical context: protection of human health, securing the satisfaction of basic needs, sustainable use of renewable resources, sustainable use of non-renewable resources, sustainable use of the environment as a sink, avoidance of unacceptable technical risks, participation in societal decision-making processes, equal opportunities, internalization of external social and environmental cost and society's reflexivity. In order to evaluate technology pathways against these types of principles, the principles have to be described by criteria that can be measured by concrete indicators (Figure 4-1). Each indicator is derived using a respective method (calculation of greenhouse gas emissions, for example, by performing a life cycle analysis). The assessment can then be performed in two ways:

- One approach is to compare the value chains against each other or against a reference value chain to find out which one is the most sustainable under the chosen principles and criteria (e.g. greenhouse gas emission reduction). Example studies are the assessment of alternative options to handle amounts of surplus renewable electricity, compared to the reference option which is curtailment of electricity (Krüger et al. 2013), or the assessment of long-term development pathways for the Tunisian electricity system, compared to the current electricity mix (Wuppertal Institut and Alcor 2012).

- Another approach is to carry out an objective-led assessment in order to determine the extent (negative, positive or no contribution) to which the implementation of the value chains contribute to certain, pre-defined sustainability goals (Pope et al. 2004, p. 604). For Germany, such goals are provided in the sustainability framework studies "Zukunftsfähiges Deutschland" (Brot für die Welt et al. 2008) or "Integratives Nachhaltigkeitskonzept" (Kopfmüller et al. 2001). The latter has been applied, for example, by (Lehmann 2013) in the context of integrated water resource management.

In any case, criteria, methods and indicators are essential for the sustainability assessment of value chains as described in chapter 4.2.

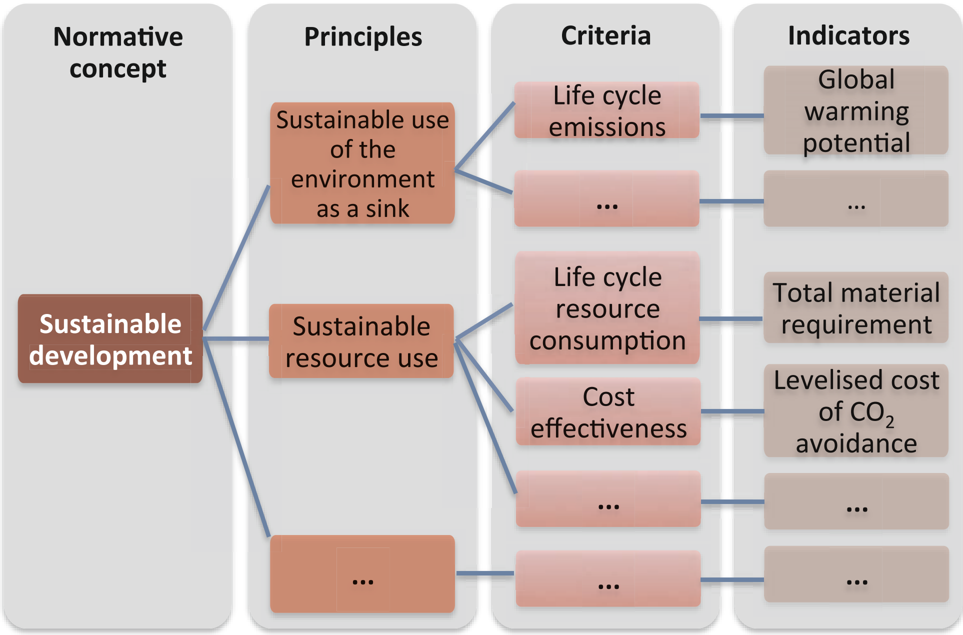


Figure 4-1: Structure of sustainability principles, criteria and indicators

A variety of methods exists to operationalize the guiding principals and assess the sustainability against the chosen criteria in an integrated manner, these include but are not limited to (SUSTAINABILITY A-Test 2006): Cost Benefit Analysis (CBA), Environmental Impact Assessments (EIP), Scenario Analysis or Multi-Criteria Analysis (MCA). Particularly suitable for an integrated sustainability assessment is the MCA as it allows to integrate quantitative and qualitative data, consider all dimensions of sustainability simultaneously and compare them in a standardised approach. This is a major difference as compared to many other methods. In a CBA for example, all values have to be transferred into monetary values, which is difficult to accomplish especially for qualitative factors such as acceptance. EIP on the other hand focuses primarily on the environmental dimension of sustainability while economic and social components can only be integrated to a limited extent. Therefore, a brief overview on the MCA as methodology to potentially support future decisions on selected value chains is presented in the following discourse.

4.1.2 Brief discourse on MCA as an overall methodology to support decisions on value chains

The strategic decision among different value chains for the utilisation of CO_2 which comprise different technology options, spatial distances and end uses, involves multiple actors and requires the consideration of a range of technical, environmental, social and economic factors. MCA methods are considered to be particularly suitable to assess these types of decision problems. They are based on a powerful analytical framework which helps to integrate qualitative and quantitative data, structure the decision making process and enhance transparency. They allow for stakeholder participation in all steps of the decision-making process.

Including stakeholder perspectives in the criteria selection, weighting and aggregation process supports a broader and deeper understanding of the decision-making context, resulting in better and commonly negotiated decisions. Despite these methodological advantages of integrating stakeholders, the analytical capabilities of the MCA approaches can also help to enable stakeholders to better understand the complexity of the decision and think about their priorities and expectations.

For the application of MCA methods, it is important to recognize that the term MCA does not describe a single approach but summarizes various formal approaches that evaluate information using mathematical algorithms and software support, providing a ranking of different strategy options. Despite differences across the various MCA methods, the basic structure of the analysis is comparable, as all methods include a number of necessary consecutive steps. Figure 4-2 gives a schematically overview of this process.

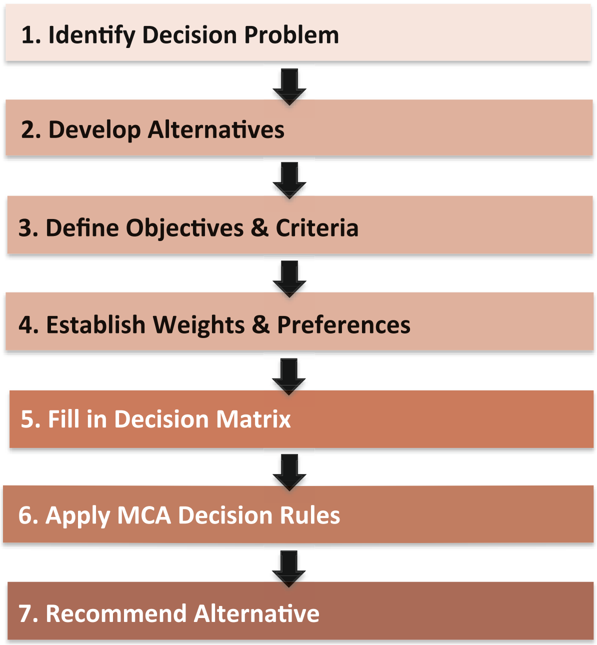


Figure 4-2: Structure of the MCA process

In general, an MCA starts with a precise identification of the decision problem where the MCA should be applied to (step 1). Step 2 develops alternatives which help to solve the problem. Step 3 specifies the objective(s) and the criteria set to be applied to the alternatives. Determining the criteria set is a critical step as the choice of criteria can have a significant impact on the outcome of the analysis. So far, no clearly defined rules for selecting criteria exist, and criteria selection is highly depending on the decision-making context.

With regard to the current study, the decision problem could be the question how to reduce CO_2 emissions from industrial sites. As alternatives, different value chains for the utilisation of CO_2 might be provided. The following objective would be to compare the alternatives to identify the most sustainable ones under a given sustainability framework. Some suggestions for criteria that may be applied are given in section 4.2.

In step 4 weights, which express priorities and preferences of various stakeholders or give priority to different sustainability dimensions, can be established. The higher the weight, the greater the importance of the criterion for the decision (Malczewski 1999, p. 177). Incorporating a wide range of perspectives and values can lead to a broader and deeper understanding of the decision-making context and help to enable stakeholders to realize and understand the complexity of the decision potential supporting a commonly negotiated and accepted decisions. In the step 5, each alternative option is evaluated against all criteria. The evaluation can be based on a scientifically sound basis by using established assessment methods to individually calculate each indicator. The result of this step is the so-called decision matrix (Figure 4-3).

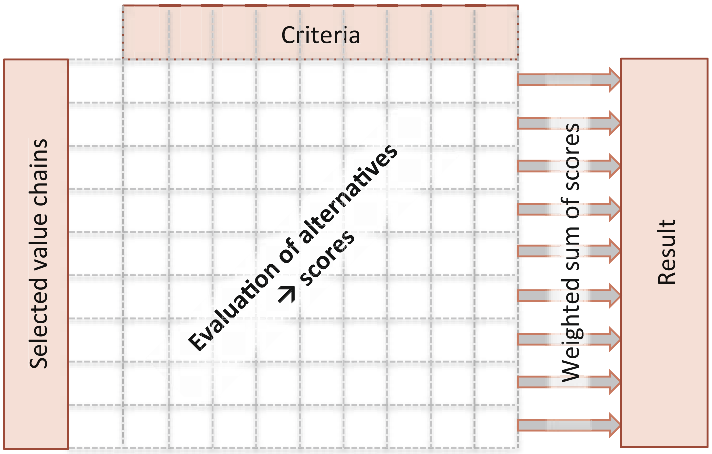


Figure 4-3: Decision matrix
Source: (Krüger et al. 2013)

The decision matrix is the starting point for the application of different mathematical MCA assessment procedures (step 6). As there exists no perfect method permitting to determine the most recommendable strategy, it is suggested to conduct more than one MCA and compare the results before making a decision (Hobbs and Horn 1997, p. 1585; Løken 2007, p. 357). This allows evaluating the alternatives on a broader foundation and eventually making better decisions. The methods most commonly applied are additive methods such as the Simple Additive Weighting Method (SAW), the Multi-Attribute Utility Theory (MAUT), the Multi-Attribute Value Theory (MAVT), or the Analytical Hierarchy Process (AHP) developed by Saaty (1980) that applies the principle of pairwise comparison. These methods are all based on an additive score aggregation. This means that the scores of all criteria are summed up, resulting in a total score for each alternative. The alternative with the highest total score is considered the best course of action.

Since good performance in one criterion may offset a poor performance for a different criterion, these methods are “compensatory” and can only be applied for the concept of *weak sustainability*. In order to operationalize a *strong sustainability* concept, non-compensatory MCA techniques are often applied. The most important group of non-compensatory MCA techniques are the outranking approaches. These methods have been developed since the late sixties; the best known are the ELECTRE family (Benayoun et al. 1966; Roy 1991) and the PROMETHEE family (Brans et al. 1984, 1986; Brans and Mareschal 2005). The result of all MCA techniques provide a ranking of the most suitable strategies. These rankings can be used to inform and support the decision-making process. Before making the decision, the robustness of the results should be ensured by conducting sensitivity analyses.

Finally, in step 7 the results and recommendations to the decision maker are provided, including a description of the whole process, the used data and methods and the chosen criteria.

4.2 Potential criteria for assessment of value chains for the utilization of CO_2

The aim of this chapter is to present selected examples for criteria and methods usually used for technology assessment. They are easily adaptable for the assessment of value chains for the utilisation of CO_2. They might be used as individual criteria and indicators when performing an MCA (see chapter 4.1), but could also be used independently for a simplified comparative analysis. Indicators may be given as numerical values (e.g. kg CO_2), as an ordinal number of an ordered set of numbers (e.g. 8 in a range of 1...10), or as textual description (e.g. “better, worse”).

A prerequisite for comparing quantitative indicators of different value chains is that they refer to the same basic unit, also called „functional unit“ (FU). In our case the FU could be “*1 kg of CO_2 avoided*“, referring to the net CO_2 reduction enabled by a combination of one out of “*n CO_2 capturing processes*” and one out of “*m reuse processes*”. Then the assessment methods described below will indicate which of the considered *“n · m value chains*” will perform best under the respective assessment criteria. The reuse processes could, on the one hand, consider the substitution of industrially used CO_2 from fossil resources by CO_2 that is captured from industrial sites or power plants (for example, during the polymer production process). On the other hand, additional processes may be necessary to balance, for example the delivery of hydrogen in case of production of methanol.

The reference case to which all of the value chains are compared is “Release of CO_2 to the atmosphere”, which describes the current situation. Splitting up the assessment results into the different parts of the analysed value chains enables valuable insights into the “hot spots” which may be considered in detail later on (so called “contribution analysis”).

Table 4-1 gives an overview on possible assessment criteria. Criteria that are marked italic will be described in detail in the text (the number refers to the respective example).

Table 4-1: Overview on possible assessment criteria for value chains for the utilisation of CO_2

Technology	**Ecology**	**Economy**	**Policy and Social**	**Systems orientation**
Commercial availability (1)	*Life cycle emissions (2)*	*Cost effectiveness (4)*	Conformance to political targets	*Systems compatibility (5)*
Innovation potential	*Life cycle resource consumption (3)*	Export potential	Independency from others measures	*Possible role as mitigation option (6)*
Market potential	CO_2, GHG emissions		Employment effect	
Usability in other fields	Risk in case of mishandling		Social acceptance	
Infrastructure requirement	Irreversibility		Stakeholder analysis	
Technical risk			Drivers and barriers	
			Legislation requirements	

Source: based on (Krüger et al. 2013; Viebahn et al. 2010, 2012; Wuppertal Institut and Alcor 2012)

Criterion 1: Commercial availability (Technology)

Indicator:

Year in which commercial availability is expected to be reached

Methods:

The term commercial availability refers to the time when a complete value chain could be in commercial operation. In our case it would refer to capturing CO_2 from power plants or industrial facilities, its purification, compression, transportation and its use in the considered chemical production processes. The assessment is usually based on screening publications and conducting expert interviews on the current state and expected course of development of the respective technologies in the years ahead.

Criterion 2: Life cycle emissions (Ecology)

Indicator(s):

Midpoint indicators usually used in LCA and related to a functional unit (FU), for example the *Global warming potential* (GWP) in <kilogram CO_2-eq/FU>, the *Acidification potential* (AP) in <gram SO_2-eq/FU>, the *Stratospheric ozone depletion potential* (ODP) in <microgram CFC-11/FU>, or the *Abiotic depletion potential (ADP)* in <gram antimony/FU>.

Methods:

In order to assess the possible *environmental impacts* of selected technologies or value chains, often the method of life cycle assessment (LCA) according to ISO 14 040/14 044 is used. "LCA addresses the environmental aspects and potential environmental impacts (for example, use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal" (ISO 14 040). Several software tools including comprehensive databases of technical processes exist for performing an LCA.

The *first step* of an LCA, the "goal and scope definition", is to address the system's boundaries, its level of detail, the subject of the LCA study as well as its intended purpose. The *second step* compares the material and energy flows that enter a system, are converted there and leave it in a different form (input/output balance, "life cycle inventory analysis", LCI). The LCA thus examines all the material and energy flows caused by a single product, beginning with the extraction and processing of the raw materials and following the process through manufacturing and use to the product's eventual disposal (the "cradle-to-grave" approach). The *third step* is to calculate the environmental impacts of the assessed flows. During this "life cycle impact assessment" (LCIA) it is necessary to "weigh up, aggregate, or generalise flows of different materials in different environmental media with different environmental impacts" (Schmidt 1997). Many methods exist to perform an LCIA, for example method *CML 2001* (Guinée et al. 2002). By applying the results to a functional unit, different production processes and the best technology can be selected with regard to an impact category. In the *final step*, the "life cycle interpretation", the results are discussed and serve as a basis for recommendations and political consultation. In technology assessment, often the specifications of future technological processes are not given. In this case, a *prospective LCA* will be performed by adapting the most important parameters in LCA of existing technologies.

Example:

Prospective LCA of Potential Future CCS-based Coal-fired Power Plants in China

In the research project CCSglobal, the global prospects of carbon capture and storage (CCS) technologies in emerging countries were explored. As part of an integrated assessment a prospective LCA of potential future CCS-based coal-fired power plants was performed. While Figure 4-4 illustrates the overall reduction rates of GHG emissions in the case of a CCS based pulverised coal power plant in China (including a contribution analysis), Figure 4-5 shows the development of the acidification and the eutrophication potential for different power plant types (without/with CCS).

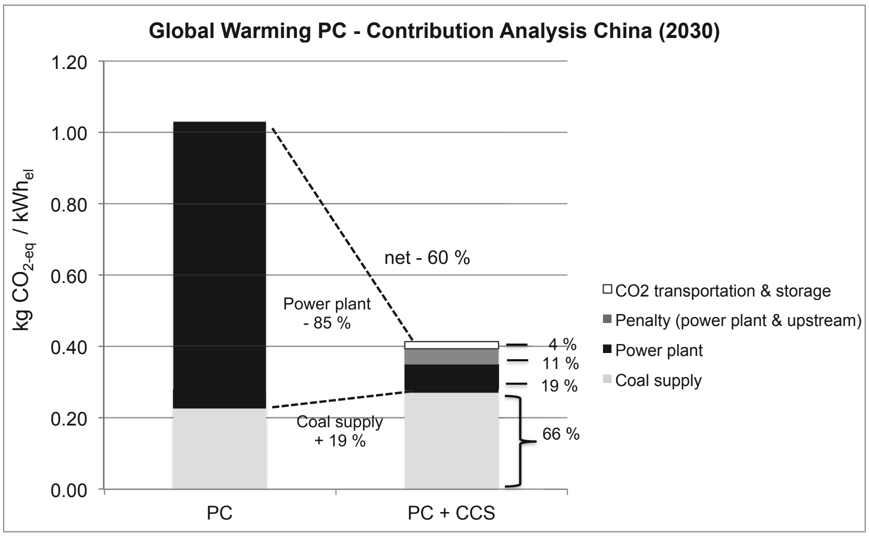


Figure 4-4: Contribution of individual life cycle phases to the global-warming potential for pulverised coal power plants (PC) with and without CCS in China in 2030

Source: (Viebahn et al. 2012)

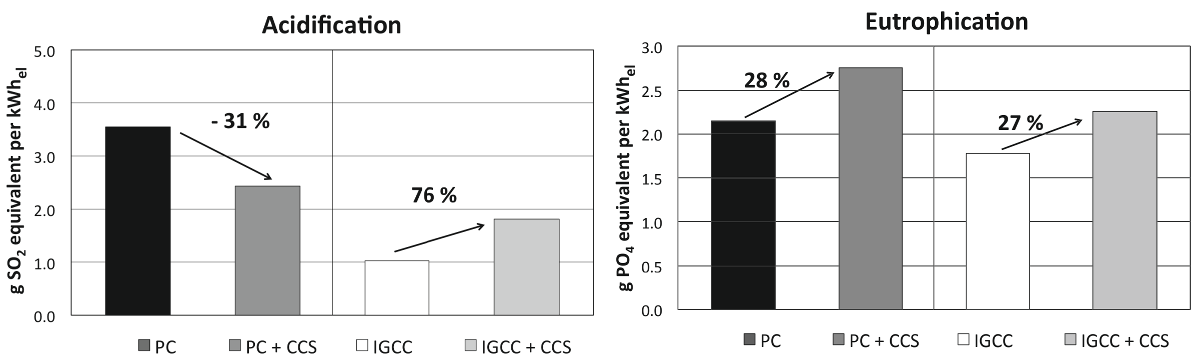


Figure 4-5: Results of selected non-GHG impact categories for PC (pulverised coal) and IGCC (integrated gasification combined cycle) power plants with and without CCS in China in 2030

Source: (Viebahn et al. 2012)

Criterion 3: Life cycle resource consumption (Ecology)

Indicator(s):

Abiotic depletion potential (ADP) in g antimony/FU, Material input per service unit (MIPS) in kg material/FU

Methods:

In some cases it is necessary or desirable to assess explicitly the resource consumption or the resource constraints caused by selected technologies or value chains (Geibler et al. 2011). This can be done either by performing a conventional LCA as described in the example for Criterion 2 and selecting the ADP as relevant indicator. A more comprehensive indicator is the material input per service unit (MIPS) (Schmidt-Bleek 1998). MIPS is based on a material intensity analysis (MAIA) and follows the logic that all inputs in a production and consumption system are finally converted into outputs with environmental impacts. While the indicator cannot offer insights into chemical environmental impacts, it directly reveals impacts connected to the absolute mass of extracted material such as lowering groundwater table, translocation of fertile soil or landscape changes (Bringezu et al. 2003). In order to calculate MIPS, all material inputs along the whole life cycle of a product need to be examined. As compared to common LCA practice, it additionally considers economically unused resource extraction. For abiotic resources, this includes for example overburden in mining industry, excavated soil during construction of infrastructure, or land loss through erosion. When it comes to biotic material, e.g. the whole plant including roots, leaves, and branches – irrespectively if they are economically used or not need to be accounted for. Figure 4-6 depicts all resource flows relevant for MIPS calculation.

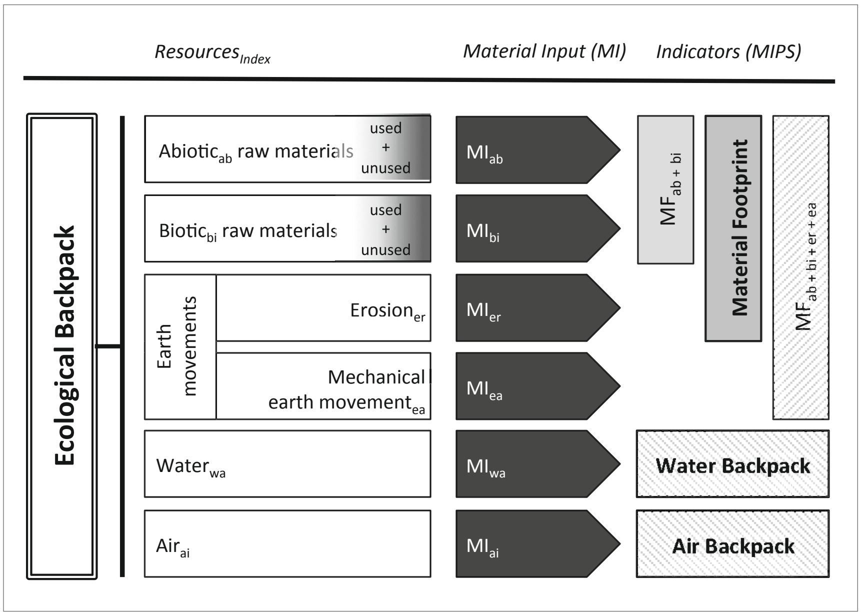


Figure 4-6: Resource categories and indicators of MIPS

Source: (Liedtke et al. 2014)

All in all, MIPS reduces the amount of data needed and therefore the complexity of LCA, since the method only requires input flows which are mainly covered by financial accounting systems (Geibler et al. 2013). While output-indicators are often difficult to understand for non-scientists, MIPS results allow a facilitated communication e.g. in form of material footprint.

Example:

Resource Use of Deep Sea Offshore Wind Farms

In order to reach the objective of the German government to generate 40 % of its electricity from renewable sources by 2030, the construction of deep sea offshore wind farms is necessary. A technology assessment of the offshore wind farms "Alpha Ventus" and "Bard Offshore I" in the north sea conducted by (Wiesen et al. 2013) shows that, compared to an onshore scenario, offshore wind farms have higher specific resource consumption. However, in comparison to the resource consumption of other energy systems, both technologies are resource efficient.

Criterion 4: Cost effectiveness (Economy)

Indicator:

Levelised cost of CO_2 avoidance (LCO) in EUR/FU

Methods:

In order to compare different technology options of different cost structures with each other, often the long-term development of their levelised cost is considered. The assessment is built upon two main methodological principles: *Firstly*, cost are made comparable by discounting them to the presence (net present value method). Thereby, all important cost parameters, such as capital cost and variable cost like operation and maintenance (O&M), service, repairs and insurance payments, must be defined and quantified. In some cases, also the external cost are included. All expenses during the plant's lifetime are divided by the product manufactured or avoided during the same time (capacity). The levelised cost of CO_2 avoidance is calculated using the equation below.

In our case the expenses describe the cost occurring through the different value chains for the utilisation of CO_2. The capacity represents the amount of CO_2 totally avoided over the lifetime of the plant. It goes without saying, that earnings enabled by avoiding the production of new CO_2 are also included in the balance.

$$LCO = \frac{(C_{Cap} + C_{O\&M}) \cdot af}{capacity} + C_{TS}$$

where

$$af = \frac{I \cdot (1+I)^n}{(1+I)^n - 1}$$

and

LCO	levelised cost of CO_2 avoidance	[LCO] = EUR/FU
C_{Cap}	capital expenditure	[C_{Cap}] = EUR
$C_{O\&M}$	specific operating and maintenance cost	[$C_{O\&M}$] = EUR
af	annuity factor	[af] = %/a
I	real interest rate	[I] = %
n	depreciation period	[n] = a
C_{TS}	specific cost of CO_2 transportation and storage (only in the reference case)	[C_{TS}] = EUR/FU
capacity	amount of CO_2 totally avoided over the lifetime of the plant	[capacity] = FU

Secondly, the assessment uses learning rates to project a long-term cost development. An experience curve describes how unit cost decline with cumulative production. The progress of cost reduction is expressed by the progress ratio (PR) and the corresponding learning rate (LR). LR and PR are usually derived from historic data or must – in case of a new technology – be estimated by considering advanced existing technologies, similar to the technology to be assessed. As in the first step, levelised cost are calculated for future years by discounting them to the year for which the LR is applied.

Both, the current and the future levelised cost of CO_2 avoidance are not only useful to compare different CO_2 reuse technology options with each other, but also to compare this distinct CO_2 avoidance measure with other low-carbon options. In case another commercially available option avoids CO_2 emissions by lower cost, the difference to the cost of the considered value chain illustrates the margin the new technology must become more economical during research and development.

Example:

Economic Potential of Carbon Capture and Storage (CCS) in Germany

In the research project RECCSplus, the potential role of carbon capture and storage (CCS) in Germany was explored. As part of an integrated assessment, future levelised electricity generating cost (FU = 1 kWh electricity) of newly built CCS based power plants were estimated and compared with the cost of renewable electricity generation (Figure 4-7).

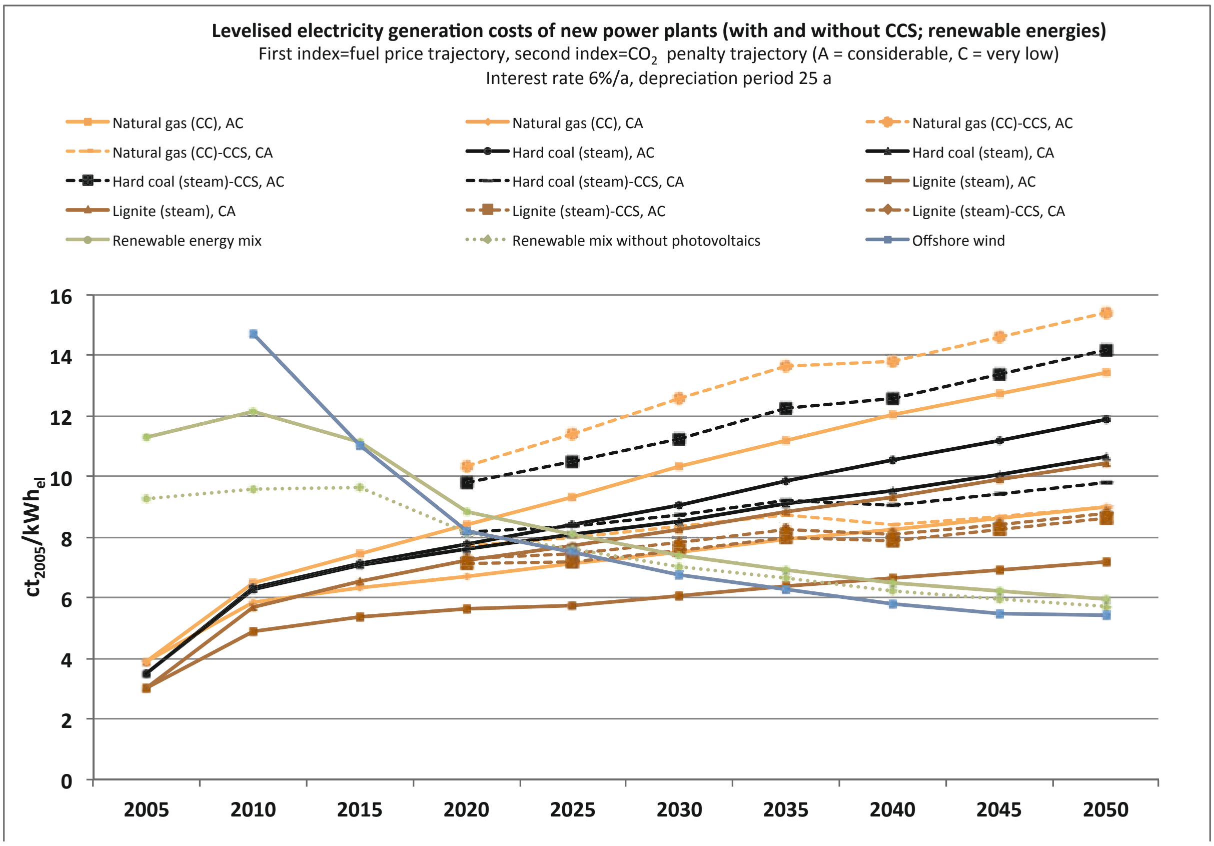


Figure 4-7: Development of future levelised electricity generating cost (new plants) for renewable energies and fossil fuel-fired power plants (with/without CCS) for price trajectories A/C and C/A (CCS from 2020, including transport and storage)

Source: (Viebahn et al. 2010)

Criterion 5: Systems compatibility (Systems orientation)

Indicator:

Ordinal number of an ordered set, depending on the compatibility with the existing industrial systems structure (e.g. 1 = very improper, 10 = fit and proper)

Methods:

The potential role of reusing CO_2 largely depends on how the targeted processes match both existing industrial strategies and the current German climate protection strategy. On the one hand, the potential depends on the existing industrial structure and previously selected industrial strategies. These can be, for example, the assumed industrial growth pathways in NRW, which might be derived from the current ongoing structural change in the German economy combined with targets from the national government or the respective industries (Schneider et al. 2014). Furthermore, assumed future technology pathways for the respected industry must be considered. The term “compatibility” refers to the grade, the considered value chains do fit into these strategies and pathways. On the other hand, possible structural changes in the future resulting from the climate protection strategy have to be taken into account. For example, the ongoing Energiewende will lead to less and less large CO_2 emission sources which will influence the number and location of possible facilities for reusing

CO_2. The assessment is usually based on interviews to be conducted with the appropriate industry, on screening publications and on scenario analysis in the field of low-carbon industry (see example 6).

Criterion 6: Possible role as mitigation option (Systems orientation)

Indicator:

Ordinal number of an ordered set, depending on the significance value chains for the utilisation of CO_2 may contribute to long-term climate protection targets (e.g. 1 = very small contribution, 10 = very large contribution)

Methods:

The possible role of reusing CO_2 as mitigation option depends on the specific and the absolute CO_2 reduction potential. First, the specific reduction potential of each value chain is analysed by comparing the CO_2 emissions resulting from the considered value chain with the emissions of the reference case. The result strongly depends on the original CO_2 source which is avoided through reusing CO_2 and on the duration CO_2 is avoided from release to the atmosphere. The relation to the avoidance potential of other carbon-mitigation technologies. A scenario analysis can be used to estimate the amount of CO_2 emissions that could potentially be avoided by capturing CO_2 from power plants or industrial sites and reusing them in the industry by application of different value chains. Scenarios provide a range of possibilities that can be used in decision-making. They can be described as “a hypothetical sequence of events constructed for the purpose of focusing attention on causal processes and decision points” (Kahn and Wiener 1967). In regard to climate policy, scenarios generally demonstrate the potential future developments of energy systems under given assumptions and targets like the reduction of greenhouse gases by 2050. In our case, industrial scenarios would have to be developed as done in (Schneider et al. 2014), being part of long-term national energy and climate protection scenarios. The scenario analysis would help to determine to which extent the total reduction potential of reusing CO_2 could contribute to the German CO_2 reduction goals, in comparison to other mitigation strategies.

4.3 Milestone: Set of criteria for the assessment of value chains for the utilization of CO_2

Table 4-1 (see chapter 4.2) illustrates a possible set of assessment principles and belonging criteria for the assessment of value chains for the utilisation of CO_2.

5 Current perception of CO_2 reuse

The successful implementation of a new technology depends beside technical, economic and other aspects to a certain degree on the stakeholders' and public approval or opposition. As for example shown by the case of Carbon Capture and Storage (CCS) technologies: "*One important reason why CCS has not yet been implemented in Germany is the lacking public acceptance of CO_2 storage.*" (Schumann et al. 2014). CO_2 reuse technologies are strongly interrelated to CCS technologies, since the captured CO_2 can be used on a large scale in different fields of application instead of storing the CO_2, as shown beforehand. CO_2 reuse technologies linked up with CCS topics could either be emerged as advantage regarding the acceptance or also as disadvantage, especially if CO_2 reuse were seen as "fig leaf" to proceed further on with the use of fossil resources. However, the potential effects on the acceptance and perception of CO_2 reuse technologies caused by CCS connotation are still barely explored, just as all the other possible influencing factors. Therefore, the perception of CO_2 reuse technologies has to be examined carefully during the current and forthcoming technical and economic implementation.

Hence, this survey on the current perception of CO_2 reuse for the first time provides a fundamental database on the existent studies on public awareness, perception and acceptance of CO_2 reuse within the English- and German-language publications. The database was gathered by an online search with selected catchwords (e.g. CO_2 reuse, use of CO_2) and examined with a qualitative content analyses (see chapter 5.1). To explore the awareness, perception and acceptance of CO_2 reuse from the perspective of policy maker several statements, party platforms, strategy papers and conference materials were scrutinized (see 5.2). Analogously to the analysis of policy maker the perceptions on selected societal stakeholder (e.g. journalists) regarding CO_2 reuse technologies were explored in chapter 5.3. In a following step the whole database and its results were additionally analysed with regard to their implications to appropriate communication methods and tools on CO_2 reuse technologies. Therefore the subchapter 5.4 extracts the apparent communication lacks which were stated out by different stakeholders and/ or described within the analysed material. The chapter closes with general information on the public awareness, perception and acceptance of CO_2 reuse and with communication methods and tools derived from the existing material (see 5.5).

5.1 Studies on public awareness, perception and acceptance of CO_2 reuse

According to the project description the survey should place emphasis on results related to North Rhine-Westphalia (NRW). But no NRW-specific data could be gathered within the scope of the online search. The following results pertain to Germany, different EU countries, especially the United Kingdom, or other countries, worldwide.

Semi-structured interviews with different key actors, targeted on policy maker and on representatives of environmental organisations, business ventures and networks from NRW would help to close the knowledge gap on public awareness, perception and acceptance of CO_2 reuse regarding the NRW perspective. These interviews are not yet realized, but could be done within the further context of follow-up projects.

The analysed data were published online on different information sources. To identify the data two different methods were used: at first the following 20 search items were read in to a web search engine (Google):

- CCU Kohlendioxid Meinung,
- perception,
- CO_2 reuse acceptance / attitude / experience,
- reuse carbon dioxide perception / acceptance / attitude,
- CO_2 capture reuse perception / acceptance, attitude,
- CCU perception carbon / acceptance carbon / attitude carbon,
- carbon utilisation perception / acceptance / attitude,
- carbon recycling perception / acceptance / attitude.

The above listed search items were translated from English into German and then also read in to the web search engine. Secondly, documents (research documents, position papers, statements, strategies and conference/ workshop papers) were searched directly on specific homepages, which were seen as highly relevant to source the stakeholders' views (scientists, politicians, environmentalists, journalists, entrepreneurs) on CO_2 reuse technologies, especially for NRW but also in a broader context. The online search was conducted in October 2014, an update was made in January 2015. In sum, only 24 documents on public awareness, perception or acceptance of CO_2 reuse were found, which constitute the basis material for the present analysis. The data analysis was carried out by variables with a direct relation to the content, that means more formal variables (e.g. name of source; date of publication; type of article) were not specified, although these information are clearly evident via the linked bibliography. The 'content variables' differentiate into the current state of research on public awareness, perception and acceptance of CO_2 reuse and into statements from/ on decision maker and stakeholder towards CO_2 reuse. Also the identified communication lacks towards CO_2 reuse topics were gathered systematically. The database was not coded and analysed with a statistical programme, since the number of cases is to small to make statements being based on statistical analyses. Therefore, the results have a more exploratory character and must be interpreted as hypothesis for further research activities on public awareness, perception and acceptance of CO_2 reuse.

The results of the content analysis reveal that "*(…) to date there has been very little systematic research into public perceptions of the technology*." (Jones et al. 2014) This is a statement of one of the first small pilot studies on public perception of CO_2 reuse within the U.K., designed to test a methodology for investigating public perceptions of Carbon Dioxide Utilisation (CDU) and elucidate new understanding of people's attitudes towards the technology. The design of this study is geared to employ more discursive and structured methods of attitude assessment within this research topic, rather than using a questionnaire-based survey to reach a high number of cases. (Jones et al. 2014)

Furthermore, there are worldwide a couple of running or planned projects on public perception of CO_2 reuse (DG JRC and DG CLIMA 2013). The *enCO2re_project* is one of these projects, which will put light on public hesitation against acceptance of new technologies besides the technical challenges of logistics and pre-treatment of industrial CO_2 rich gas streams for catalytic or fermentation reactions. The main activities regarding these topics are investigated by the Institute for Advanced Sustainability Studies e.V. (IASS Potsdam), RWTH

Aachen University and Bayer MaterialScience (BMS Germany). Within this project also a consultation with stakeholders on CO_2 reuse should be include public perception and acceptance concerns, as there is an increasing interest by industrial companies for research in the field of strategic communication with external stakeholders. The project aims to encourage entrepreneurship culture as well as taking care of public awareness through successful target-group oriented communication and dialogues and executive training. Hence, the enCO2re_project will cover development of guidelines for strategic communication on CO_2 reuse to ensure public acceptance (Climate-KIC 2014). Beside this project the Carbon Dioxide Utilisation Network (CO_2Chem) has developed a research sub-theme around the area "Public Perception of CDU" with plans to emerge the research on public perception of CO_2 reuse. (CO2Chem 2014)

Specific research results on public perception of CO_2 reuse of the two latter activities are at present obviously not accessible using an online search. Whereas the results of the above mentioned pilot study are stated below supplemented by results and statements conducted away from the whole database, which includes also non-academic references (e.g. strategy papers, conference proceedings or newspaper articles, blogs). The following description of the results falls into three categories: the awareness of CO_2 reuse technologies, the pros and the cons, distinguished between the different CO_2 reuse technologies, if possible.

1) Awareness and perception of CO_2 reuse technologies

Research results regarding the awareness of CO_2 reuse technologies are barely existent, so far. According to (Jones et al. 2014), the initial awareness of CDU was very low among the participants of their pilot study. Another result of this study illustrates the existence of different preferences in dependence on several CDU options (Jones et al. 2014). This is an important point regarding future research activities, since there is probably more than one concept on public awareness, perception and acceptance of CO_2 reuse technologies which has to be explored.

2) Supporting Arguments (pros) for CO_2 reuse technologies

Within the analysed data the following arguments were stated out to lead the debate on CO_2 reuse technologies in a more positive or at least neutral direction regarding public awareness, perception and acceptance issues.

In general the CO_2 reuse technologies could be seen as one possible solution to limit the CO_2 emissions (Jones et al. 2014). To some extent, the participants of the pilot study saw the CO_2 reuse technologies as a "*symbolic of attempts to address climate chance, although few believed that it was the 'answer' to climate change*" (Jones et al. 2014).

Beside these effects on climate protection the results of the pilot study indicate that people believe that CO_2 reuse technologies will have economic benefits in terms of creating useful products and job opportunities (Jones et al. 2014).

As mentioned before, the awareness and perception of CO_2 reuse technologies could strongly be linked with these issues on CCS. Hence, a majority of arguments within the analysed documents deals with more positive effects on CCS acceptance through CO_2 reuse technologies. (Hoppe 2014) and (Kruse et al. forthcoming) announced, as the public acceptance for CO_2 storage (esp. on-shore storage) is due to perceived storage risks not yet given in many countries, the reuse of CO_2 might be a more promising solution and this argument was, according to (Kruse et al. forthcoming), often published in public debates. Researchers from the University of Sheffield and the Energy Research Centre of the Netherlands said that CO_2 reuse technologies *"(…) could overcome many of the drawbacks of carbon capture and storage, including the difficulty in finding enough underground storage space, the possibility of leakage, long-term liability issues, and problems with public acceptance.*" To state it more precisely, they suggest to create a specific value by means of CO_2 reuse technologies, this would help to offset the costs of CCS. Furthermore, they see enormous benefits of "reversing combustion" or "closing the cycle" on CO_2. (Lavelle 2011) The Global CCS Institute explained that the CO_2 reuse technologies can provide a number of benefits common to both developing and developed countries. Especially the use of EOR (Enhanced Oil Recovery), as one specific physical CO_2 reuse application form, could gain storage learning and develop public acceptance of CO_2 storage. (Global CCS Institute and Parsons Brinckerhoff 2011)

A further research step was done within the scope of the pilot study from (Jones et al. 2014). The researcher compared the perception of CO_2 reuse technologies with the perception of CCS and stated: *"(…) The only CDU option to be more favourably evaluated than CCS was cement production. Arguably this is because participants saw cement production as a process that would both make use of CO_2 and fix the carbon indefinitely.*" This result could indicate a kind of a public imperative; that CO_2 reuse technologies probably have to close the cycle on CO_2, if the public should accept these new technologies.

The analysed data revealed one more supporting argument for CO_2 reuse technologies, besides the already mentioned climatic and economic effects as well as CCS and CO_2 storage topics. This argument refers to the fuel synthesis (Power-to-Gas/Fuel with renewables), which could led the debate on CO_2 reuse technologies in a more positive direction. A researcher from the U.S. Department of Energy's Sandia National Laboratories said within an interview (Lavelle 2011): "*We could have a technology that could produce the same fuels we get from petroleum and preserve today's infrastructure. (…) fuels that could go into the vehicles of today as well as the ones of tomorrow.*" In addition, (DG JRC and DG CLIMA 2013) indicated within a CO_2 reuse workshop proceeding, that higher costs, caused by the process of fuel synthesis, do not generate a negative effect regarding the awareness and perception of this fuel and technology. Also (Gareffa 2013) reported that another study said, the drivers would even pay more for vehicles with carbon-capture technology (a more or less theoretical idea of a vehicle with on-board technology that captures carbon emissions for later storage or reuse). But (Kruse et al. forthcoming) point out the necessity of a transparent communication regarding the potential CO_2 reductions of the fuel synthesis, because such a communication would improve the acceptance on the new products.

3) Contra Arguments (cons) for CO_2 reuse technologies

Within the analysed data there were also mentioned some arguments, which could have a negative impact regarding public awareness, perception and acceptance issues on CO_2 reuse technologies.

The (carbon capture journal 2013) faced with a "*wide range of obstacles to commercialisation for CO_2 reuse technologies, including successful demonstration of the technology itself i.e. overcoming R&D challenges, and also external factors, such as competition from alterna-*

tive services and goods and also the public acceptance". Although there were no specific influencing factors on the public acceptance stated out within this article, within the above mentioned pilot study Jones et al. (2014) detected a scepticism over the long-term impact of the technology in tackling climate change. Furthermore, their results indicate that people are apparently least favourable to technical options which are more obviously related to facilitating current wasteful lifestyles, such as a reliance on oil through EOR, plastics and carbon-based transportation. In particular other CO_2 reuse technologies options beside cement production were likely to be seen as only delaying (and in the case of EOR increasing) an inevitable release of CO_2 to the atmosphere. It is reasoned that any investment should target behaviour change campaigns to reduce energy use rather than technological fixes, like CDU. (Jones et al. 2014)

Arguments which reinforce these results come from a technical staff member at the U.S. Department of Energy's (DOE) Los Alamos National Laboratory and bear on fuel synthesis. He said the benefits of the CDU approach will be limited unless the energy to create the hydrocarbon fuel comes from a source other than the burning of more fossil fuel (Lavelle 2011). Kruse et al. (forthcoming) pursue this argument and specify, that the production of fuel synthesis needs an intensive coordination of the different stakeholders. Because a plenty of new manufacturing-plants must be built and at the same time a consortium of fuel- and engine-producer together with politician have to apply another standard for the market introduction. This is essential to avoid potential rejections within the public, comparable to the incidents in Germany while introduce the benzine type E10. Herewith Kruse et al. place certainly an important influencing factor on the public awareness, perception and acceptance issues on CO_2 reuse technologies; the needed communication strategies.

The Carbon Dioxide Utilisation Network (CO_2Chem) revealed that there are some negative views on CO_2 reuse technologies and - from their perspective - prejudices based on thermodynamic aspects (CO2Chem 2012).

To sum up, the results of (Jones et al. 2014) pilot study illustrated, that his preliminary research and also the above mentioned and consolidated arguments suggest, that the concept of CO_2 reuse technologies is not rejected by people so far. But the concept of CO_2 reuse technologies is greeted with caution in terms of awareness and acceptance. It can be assumed, that a majority of the public have never heard on CO_2 reuse technologies or have heard about it just a little bit. Influencing factors of public awareness, perception and acceptance of CO_2 reuse technologies are still unknown. The above mentioned pros and cons pertain to very different social areas of life (lifestyle, environmental and economic influences, mobility), since the CO_2 reuse technologies have a wide range of application fields. Hence the analyse of influencing factors regarding public awareness, perception and acceptance of CO_2 reuse technologies has to tackled very elaborately.

5.2 Decision maker policy

The analysed articles and documents report on the politicians' view on CO_2 reuse technologies and also on concrete requirements to them. Right now, obviously no relevant research results are existent, which could deliver first explications on that. Anyway, the results give first insights into the awareness of decision maker on CCU.

The Carbon Dioxide Utilisation Network (CO2Chem 2012) pronounced a lack of governmental buy-in and awareness of CCU processes. The debate within the media on CO_2 reuse technologies in the U.K. seems to be quite advanced compared to the German or the U.S.. The Guardian (Harvey), a British national daily newspaper, printed an interview. The presented arguments within this interview foster the investment in R&D for carbon capture and utilisation. Furthermore, the Government has to be made aware on the need of the potential benefits of the technology so that barriers can be brought down, especially regarding potential investors. A researcher said: "*Our report shows that all CCU options could be relevant to the UK and given its business-oriented academic community, the UK could benefit from the commercialisation of the technologies involved.*"

The European Commission (EC) also wishes to build a strategy that implements CCU in Europe on the long term. To create a long term strategy, the following aspects are important for the EC: raising awareness, communication, establishing networks and building coalitions. The EC sees different ways of addressing these aspects, one is the own reporting, estimated as a good way to reach out to policy makers at the European Commission and raise awareness for CCU technologies. (Hendriks et al. 2013 p. 79)

A staff member at the U.S. Department of Energy (DOE) Los Alamos National Laboratory, coauthor of a white paper on carbon capture from air, is more reserved regarding the possible opportunities on CO_2 reuse technologies, especially for fuel synthesis. He stated that the benefits of this approach will be limited unless the energy to create the hydrocarbon fuel comes from a source other than the burning of more fossil fuel. (Lavelle 2011)

5.3 Selected societal stakeholder

The analyzed articles and documents revealed, that most notably journalists and network stakeholders generate the debate on CO_2 reuse technologies and their joined social challenges within the last years.
Within the statements a plenty of questions and challenges linked with CO_2 reuse technologies were addressed, some arguments are even inconsistent with others. It is evident, that the public debate on CO_2 reuse technologies is in a very early stage and along the lines of the early CCS debate especially economic aspects were faced.

One of the major challenges to introduce CO_2 reuse technologies are seen in specific economic affairs. (Dodge 2014a) stated that "*the real solution lies in finding markets for CO_2*". To find those markets the CO_2 has to be converted into a family of useful products at first. Algae and mineralisation – especially for building materials - get the most media attention (Parsons Brinckerhoff and Grubnic 2011). (Dodge 2014b) said, the market for EOR is not nearly large enough to consume all the CO_2 being emitted. Make CO_2 into a commodity would raise the market mechanism and can capture the public's imagination (Dodge 2014b; Parsons Brinckerhoff and Grubnic 2011). CO_2 is a useful molecule and a basic building block of life. CO_2 can be polymerized, mineralized, used to grow plants or put to work in a variety of industrial and scientific applications. CO_2 can be converted into fuels as well, but the required energy to break the molecular bonds has to be reduced for any CO_2-to-fuels process to be effective (Dodge 2014b; Lavelle 2011). But pioneering researchers (e.g. Earth Institute at Columbia University) and entrepreneurs (USA) argue the technology is close at hand for recycling CO_2 back into fuel for use in today's engines (Lavelle 2011).

(Dodge 2014b) also exposed logistical challenges in locating pipelines to move the CO_2. This fact is seen as part of a problem, which has to be solved for introduction on the market. But with that in mind he sees a number of firms seeking to take advantage of cheap forms of energy such as industrial waste heat or desert solar to produce CO_2 fuels. Many entrepreneurs would see the opportunity in this emerging market. (Dodge 2014b)

All these assumptions imply that the given opportunities were well known by relevant political and economic stakeholders. Whereas (CO2Chem 2012) illustrated a lack of governmental buy-in and awareness of CCU processes and economic opportunities and also a general lack of awareness in public. CO_2 reuse technologies alone cannot act as a driver. A carbon price and early stage governmental support are required. (Parsons Brinckerhoff and Grubnic 2011) This statement is being composed to (Halper 2011), who stated that carbon recycling is mostly privately held, backed by investors from the U.S. and Iceland.

Besides the CO_2 reuse technologies for themselves some statements are linked to CCS. (Parsons Brinckerhoff and Grubnic 2011) stated, that reuse revenues can act as a modest offset to CCS costs, and hence will benefit early demonstration projects. The reuse technology that presently provides the largest revenue support is enhanced oil recovery (EOR).

The analysed documents reveal, that until now a discussion on the public awareness, perception and acceptance of CO_2 reuse technologies is more subordinated compared to the awareness and perception from entrepreneurs and also politicians. Hence, the point of the matter is, if CO_2 intensive industries evaluate CCU as attractive business segment. (Environmental Leader 2014)

5.4 Communication lacks

The database and their results were analysed with regard to their implications to appropriate communication methods and tools on CO_2 reuse technologies. Therefore this subchapter extracted the apparent communication lacks which were stated out by different stakeholders and/ or described within the analysed material.

The findings of the pilot study from (Jones et al. 2014) "*(…) have important implications for how communication about CDU technology within the public sphere should be framed.*" The researcher differentiate between topics which could more foster or not foster the support and acceptance of the technology. The following table gathered up the results from Jones and also the results from the other analysed data.

Table 5-1: Overview on communication lacks, regarding possible topics on CO_2 reuse technologies

Communication lack (or need)	More sensitive topics	Target group	Source
	CDU combats climate change	Public	(Jones et al. 2014)
CDU generate new employment opportunities		Public	(Jones et al. 2014)
CDU generate useful products		Public	(Jones et al. 2014)
	Risk of CO_2-products	Public (individually and	(Climate-KIC

Communication lack (or need)	More sensitive topics	Target group	Source
		country-specific)	2014)
CO_2-containing products to prepare the market entrance		Public (target-group oriented)	(Climate-KIC 2014)
Learning from CDU failure		Industry	(Climate-KIC 2014)
Managing the ambiguity of open innovation		Industry	(Climate-KIC 2014)
Life-Cycle-Assessment analysis		Stakeholder	(Climate-KIC 2014)
Implication of CO_2 technologies on prosperity		Stakeholder	(Climate-KIC 2014)
Figures on climate impact in order to build up strategic narratives		Public stakeholder	(Climate-KIC 2014)
Communicate key findings		All	(Hendriks et al. 2013)

The table revealed, that the most recommendations regarding possible topics, which should be communicated to different target groups, so far are related to economic effects on CO_2 reuse technologies. At the same time the focus lies on those aspects, which could foster the acceptance on CO_2 reuse technologies. Further details on communication lacks towards CO_2 reuse technologies could not detected within the analysed data. But there were a lot of activities in the field of strategic communication on CO_2 reuse technologies identified, which are listed below and which soon provide certainly useful recommendations on that.

The enCO$_2$re flagship (Climate-KIC 2014) will put light on public hesitation against acceptance of new technologies and the required installation of industrial infrastructure. They see an increasing interest by industrial companies for research in the field of strategic communication with external stakeholders. The flagship will cover development of guidelines for communication. In addition to the theme of technology acceptance, the flagship will explore opportunities for a multidimensional series of educational programmes, targeting students (i.e. master classes, PhDs and journeys or spark lectures) as well as executive trainings. One of the three pillars of the enCO$_2$re flagship is to take care of public awareness through successful dialogues and executive training. Referring to experience with public stakeholders showing their protest against expanding industrial infrastructure (e.g. power grid expansion, pipeline connections), this flagship will take a fundamental look at appropriate communication in order to achieve the necessary acceptance. Another important goal is the development of a target-group oriented communication to ensure public acceptance of CO_2-containing products to prepare the market entrance.

As mentioned before, also the European Commission (EC) wishes to build a strategy that impacts CCU in Europe on the long term. Topics regarding communication, establishing networks and building coalitions will be addressed in different ways . (Hendriks et al. 2013 p. 79) Reports are regarded for instance as a good way to reach out to policy makers at the European Commission and raise awareness for CCU technologies. Other CCU stakeholders could also benefit from these reports. The EC will invest in communication towards CCU stakeholders and share their thoughts and conclusions with them. These activities has resulted in the development of a website (www.CO2reuse.eu) and the organisation of a workshop. The function of the website is to communicate the key findings of the conducted studies and to offer a portal for CCU technologies in Europe. Workshops served and will serve primarily for presenting and discussing the results of the studies, but also to create a platform for stakeholders to bring together key stakeholders.

Also the RWTH Aachen und Bayer MaterialScience explore the risks and barriers regarding the communication on CO_2 reuse technologies as well as the development on communication strategies and products to initiate a debate relating to society as a whole. (IASS 2014)

The Carbon Dioxide Utilisation Network (CO2Chem 2012) has, as mentioned above, a cluster on research around the area “Public Perception of CDU”. The results were also used for current activities of the network itself in the field of public perception and communication work.

There is also a discussion on how CO_2 reuse technologies can provide lessons learned associated with CO_2 storage and can help foster community acceptance of storage. (Parsons Brinckerhoff and Grubnic 2011).

5.5 Appropriate communication methods and tools

So far, the existent research results are a good starting point for a wide range of further needed research activities on appropriate communication methods and tools regarding CO_2 reuse technologies.

The specific regarding the communication on CO_2 reuse technologies is obviously substantiated within the enormous variability of this technology. It has to be assumed, that for each technical CDU application very different patterns of awareness, use and communication will arise, according to the specific target groups from micro (individually/local) to macro level (EU).

Potential learning effects from the debate on CCS and the more advanced research in this field should be utilized. Therefore the communication on CO_2 reuse technologies should even not disregard specific topics, for example technical, ecological or scientific aspects or topics which could obviously not foster the acceptance. All topics have to be addressed detailed enough to enable the public and all stakeholders to improve their knowledge and to avoid so-called ‘pseudo-opinions’, which are not stable and hence not useful to predict the future perception and acceptance on CO_2 reuse technologies. The communication on CO_2 reuse technologies should also be embedded in a broader context of technologies related to CO_2 reductions.

Furthermore, communication strategies on CO_2 reuse technologies should include all potential risks and benefits linked with CO_2 reuse technologies. The way of representing must be “translated” to each target group, that means the prepared information must be transparent (source), well-balanced (pros and cons), comprehensible (for each group), country-specific (according to different circumstances) and accessible for everybody.

5.6 Milestone: Results from the survey about CO_2 perception

The results provide insights into the public and stakeholder understanding of CO_2 reuse related issues. There is no previous research which reveals consolidated results on public awareness, perception and acceptance of CO_2 reuse. Assumptions were made on strong comparison with Carbon Capture and Storage Technologies (CCS) and the rejections on this technology and also CO_2 pipelines. On the other hand CO_2 reuse was seen as a technical alternative to the storage of CO_2. Recommendations should be derived how to communicate CO_2 reuse in order to enable the public and relevant stakeholder to develop well-informed and well-considered opinions which are valuable predictors of future public acceptance on CO_2 reuse .

6 Recommended actions

The recommended actions are divided into three sections: 1) R&D priorities, 2) Demonstration projects and 3) Political and economic conditions. A fourth rubric sums up 4) "Comprehensive aspects for the reuse of CO_2". The first three sections are structured by the kind of use (Biomethane plants, Fuel synthesis and Industrial use) whereas the comprehensive aspects are broken down to aspects of General remarks, Ecological soundness, Systems analytical perspective and Perception. The recommended actions are summed up in Table 6-1 at the end of this chapter.

6.1 Research and development priorities

CO_2 from biomethane plants

The operation of biomethane plants is state of the art. Nevertheless, the technology could be further developed especially in terms of optimization of the fermentation process and the separation of CO_2. New approaches as the direct methanation of CO_2 within the raw biogas are to be further developed.

Industrial use of CO_2

From our today's point of view most promising future (chemical) non-captive uses of CO_2 as raw material are for the production of a) polymers and b) platform chemicals such as methanol, methane or formic acid. Platform chemicals can be used for a subsequent synthesis of chemical products or energy carriers. It seems promising to enlarge the R&D efforts in reusing CO_2 as a resource for diverse industries especially in these fields.

Existing chemical and methanol production sites are most suitable to be nucleus for the development of CO_2 use. In NRW, these production sites are close to current and potentially future industrial CO_2 sources. Necessary electrolyzers are supposed to be constructed close to these industrial sites and excess renewable electricity is transported there.

As the reduction of CO_2 to hydrocarbons is very energy intensive, efficiency improvements of the reduction processes are crucial. Research on new catalysts facilitating a direct CO_2 use (not via CO) should be enabled by public, science and business, as well as research and development on future CO_2 logistics in NRW.

Fuel synthesis (Power-to-Gas / Power-to-Fuel)

The degression of costs is a major topic for all process steps of Power-to-Gas. Two cases have to be distinguished: the production, transport and use of hydrogen on the one hand and the further methanation of hydrogen to the same quality as natural gas. For the first case, the capacity of the grid has to be explored regarding the following questions:

- To what extend can hydrogen be mixed to natural gas in the grid ("blend wall")?
- For what regions in Germany and Europe apply different blend walls?
- How can it be assured that the limits of potential concentrations are kept?

- How could the transit of hydrogen through the grid be realized (injection and redelivery of hydrogen)?

For the case of methanation the coupling of electrolyser and methanation unit with a storage unit for hydrogen has to be optimized, using storage facilities for example. The economically equilibrium of further investing in hardware and possibly full utilisation of workload has to be identified.

6.2 Demonstration projects

CO_2 from biomethane plants

First projects make use of CO_2 from a biomethane plant for the methanation of hydrogen in a Power-to-Gas process[35]. New technologies for the separation of CO_2 (driven by pressure in the fermentation reactor, for example) are under development.

For further implementation, the scale-up and the collection of CO_2 from a number of plants ("micro grid for CO_2") should be demonstrated. This issue is a challenge of infrastructure and transport, regardless of the separation technologies that are applied.

Industrial use of CO_2

A couple of projects regarding the use of CO_2 are conducted, some of them are getting to the phase of demonstration and pilot plants. Due to the uncertainties involved, industrial companies need to develop future business models to cope with the needs. The production of H_2 and the transformation of CO_2 into a future feedstock will change existing value chains. So industry should start already now to get ready for feedstock shifts and new business cases.

Fuel synthesis (Power-to-Gas / Power-to-Fuel)

At least a couple of projects regarding the use of CO_2 is conducted of which plenty are getting to the phase of demonstration and pilot plants. The further conversion to a fuel via the Power-to-Gas route is conducted more often than the use as a chemical building block.

6.3 Political and economic conditions

CO_2 from biomethane plants

The separation of CO_2 as a commodity for industrial uses could be a niche that is worth to be implemented. But after the amendment of the Renewable Energy Sources Act (EEG) in Germany in 2014, there are only low incentives for the erection and operation of biomethane plants. However, if biogas and biomethane plants are deployed in the future, access to CO_2 are to be guaranteed and opportunities for industrial use of CO_2 be analysed.

35 See the "Audi e-gas" project (accessed at 13.04.2015): www.audi.de/de/brand/de/vorsprung_durch_technik/content/2013/08/energiewende-im-tank.html

Industrial use of CO_2

Currently, there are only very few incentives for the development of alternative resources for the industry (compared to the energetic use). Under these conditions, the R&D focuses on the use of P2G as fuel or energy carrier. Thus also incentives for the development of alternative resources for the industry (CO_2 as a feedstock) should be strengthened. Within the European Emission Trading Scheme (ETS), the utilization of CO_2 is not explicitly mentioned, but by using one tonne of CO_2, one emission allowance less is needed for the emitting company. The current low price of the allowances of considerably less than 10€ per tonne does not support the costly use of CO_2 within the ETS system.

Each analysis should take into consideration that the net CO_2 reduction effect of a value chain for the utilisation of CO_2 depends - among others - on the durable fixation of the CO_2 in the released product. Therefore, effective reuse of CO_2 to substitute fossil CO_2 sources is to be supported and emphasis is needed to be put on the development of products with a long life-time. Production of methane, methanol, urea or ammonia e.g. implies not a permanent fixation of CO_2 but only "intermediate use or storage" which would partly substitute yearly fluxes of carbon. CO_2 in polymers last longer. Political funding should also orientate towards the duration of fixing CO_2 in products.

Even more important is that those process routes should be further developed and supported by policy framework conditions which provide a life-cycle-wide net reduction effect on GHG emissions and a low resource intensity. For that purpose also cross-sectoral analysis and research is required, e.g. to compare different paths of reuse as fuels, as feedstock or for heat and power.

Fuel synthesis (Power-to-Gas / Power-to-Fuel)

To be beneficial for the electricity grid, electrolysers have to be used not as base load consumers, but in an intermittent way leading to lower full load hours. These lower operation times and the possibly necessary hydrogen storage affect the economic feasibility of Power-to-Gas. Thus the framework (especially for the energy market) has to be arranged in a way, that coupling of sectors and seasonal storage via P2G can be economically feasible. Other regulatory modifications should be revised as well.

When producing methane or methanol for use as energy carriers or energy storage media (or as substitute for fossil based platform chemicals), significant amounts of CO_2 would be required. The major bottleneck, however, might be the availability of renewable energy for the production of H_2 because a lot of hydrogen is needed for the transformation of CO_2 to hydrocarbons. To stay environmentally friendly, the hydrogen has to be produced by means of renewable energies in a resource and energy efficient manner.

There could be lock-in effects if constant H_2 and thus electricity demand was created (and renewable electricity is not available at any time). The question remains how policy can ensure that physically "green" electricity is used for H_2 production by electrolysis.

6.4 Comprehensive aspects for the reuse of CO_2

General aspects

In 2011 worldwide anthropogenic CO_2 emissions lay at 34 000 million tons worldwide. Referring to the IPCC report 2007, usage of CO_2 amounts to about 178 million tons that means 0.6% of the current total anthropogenic emissions. In chemical industry there are some new applications that are in a mature R&D state to use CO_2 as polymer building block. Additionally, there is a limited potential of use that could be increased by producing methane from CO_2 and H_2. For all utilization approaches, a huge amount of regenerative energy is needed and scenarios are characterized by a lack of profitability due to the current economic and political environment and frameworks. CO_2 reuse is one important building block of a strategy to lower CO_2 emissions and R&D efforts has to be continued and intensified. But in general, CO_2 reuse has a limited potential and it has to be flanked by other activities as energy efficiency measures in households, public, industry […] as well as by R&D activities dealing with a more sustainable energy production that includes energy storage systems to ensure security of supply and development of market models to ensure competitive prices for the energy supply.

Comparative life-cycle oriented analyses are needed for the use of CO_2 and carbon rich waste which is transformed to platform chemicals (such as methanol, methane and syngas) using renewable energy such as wind power in order to determine which process chains and products are associated with the highest resource efficiency and lowest GHG emissions. The analysis should comprise cross-sectoral comparisons in order to determine whether the use of renewable energy capacities and CO_2 sources should be directed towards chemical production or transport (if e.g. renewable SNG is used for either purpose).

The estimations of the theoretical potential for CO_2 reuse vary largely (compare presented cases A, B and C in Figure 3-1). Hence, uncertainties about utilization potential and/or limited CO_2 sources should be kept in mind for the introduction of policies and measures for CO_2 mitigation.

Ecological soundness

The use of CO_2 is based on the availability of large amounts of electricity and a reasonable infrastructure to produce H_2. CO_2 reuse (including PtF / PtG) only makes sense if renewable electricity structures (generation and transport) and electrolysis infrastructure are build up at the same time in large scale. If an H_2 and CO_2-reuse infrastructure is constructed, potential lock-in effects might be created in times when renewable electricity is not available. Therefore, risks of increased fossil power use has to be taken in mind. These issues must be politically addressed.

As the capacities for renewable energy supply are limited, its use for CO_2 transformation to hydrocarbons should be directed towards those process chains and final products which provide the highest resource efficiency and least GHG emissions. Political funding should also be oriented towards these aspects.

Systems analytical perspective

Due to the complex structure of systems and relationships linked with the value chains for utilization of CO_2, a systems analytical perspective for process development and assessment is recommended. On the one hand this is of relevance to the assessment of *individual value chains* that should not focus on a single process step but apply a holistic perspective. One example is to include an Life Cycle Assessment (LCA) into the technology development process in an early stage of technology development. The LCA could focus on a set of specific impact categories including the overall resource implications in the natural system. On the other hand the compatibility of the value chains with the *industrial system and the energy system in general* is to be assessed. Performing a long-term technology foresight process enables to recognize possible chances and obstacles / limitations as well as drivers and barriers for the future implementation of the considered value chains.

Perception

Research activities on acceptance and communication regarding CO_2 reuse technologies are needed. Communication on CO_2 reuse technologies must differentiate between the specific variability of this technology and should include all potential risks and benefits linked with CO_2 reuse technologies. The way of representing must be "translated" to each target group, that means the prepared information must be transparent (source), well-balanced (pros and cons), comprehensible (for each group), country-specific (according to different circumstances) and accessible for everybody.

A multi-criteria analysis (MCA) of selected value chains for CO_2 reuse offers the chance for a broad stakeholder participation[36]. It is, therefore, recommended to involve as early as possible various stakeholders from NGOs, science, industry, economy and policy in both the design of the assessment process and in conducting the MCA. When initiating an MCA and developing its objectives it should be considered how results can be best communicated. This is especially important if results are to be communicated to society and increase acceptance for certain technologies.

[36] Since the presented study has a more explorative character, it only gives a brief discourse of the methodology with a subsequent illustration of some selected assessment criteria. Before the implementation of a full-scale multi-criteria analysis it is therefore recommended to adapt the methodology to the value chains for the utilisation of CO_2 and to develop a broad set of criteria and indicators as outlined in this study.

Table 6-1: Consolidation of recommended actions

	R&D Priorities	Demonstration Projects	Political and Economic Conditions
Biomethane plants (chapter 1.2)	State of the art, but should technologically be further developed (e.g. optimization of fermentation process; optimization and development of new technologies for the separation of CO_2)	“Audi e-gas project ”: CO_2 from a biomethane plant for methanation of hydrogen (Power-to-Gas) Scale-up and collecting of CO_2 from a number of plants (“micro grid for CO_2 “) should be demonstrated	Since amendment of EEG in 2014 only low incentives for erection and operation of biomethane plants CO_2 from biomethane plants as a commodity for industrial use could be an interesting niche If biogas and biomethane plants are deployed in the future access to CO_2 should be guaranteed and opportunities for industrial use of CO_2 be analysed
Industrial use (chapter 2)	The industrial use of CO_2 as a raw material for the production of polymers and platform chemicals (methanol, methane or formic acid) shall be further developed. R&D e.g. on new catalysts for a direct CO_2 use and on future CO_2 logistic in NRW is crucial and should be facilitated by public, science and business.	A couple of CO_2 reuse projects are conducted as demonstration or pilot plants. Industry should start already now to get ready for feedstock shifts and new business cases. As the reduction of CO_2 to hydrocarbons is quite energy demanding, the use of CO_2 as raw material should ideally be combined with measures on energy efficiency.	Incentives for the development of alternative resources for the industry (CO_2 as a feedstock) should be strengthened. Longer term fixation of CO_2 (e.g. in polymers) should be aspired and politically supported. Those routes of CO_2 reuse are further to develop and brought towards commercialisation which provide life-cycle-wide net benefits in terms of GHG emissions and resource use. For that purpose also cross-sectoral analysis and research is required, e.g. to compare different paths of CO_2 reuse as fuels, as feedstock or for heat and power.
Power-to-Fuel / Power-to-Gas (chapter 2.3)	The degression of costs is a major topic for all process steps of PtG. For the case of hydrogen production, the capacity of the grid has to be explored regarding the following questions: (1) “blend wall” of hydrogen, (2) regional differentiations in the gas grid (3) limits of potential concentrations (4) transit of hydrogen (injection and redelivery of hydrogen). For the case of methanation the coupling of electro-	A couple of CO_2 reuse projects are conducted as demonstration or pilot plants. Projects with Power-to-Gas route are more often than the use as a chemical building block	Concepts and political framework need to be developed to allow economic feasibility regardless of intermittent operation mode of electrolysers and necessary hydrogen storage. Also other regulatory modifications should be adapted to enable the coupling of sectors and seasonal storage via P2G. To avoid lock-in effects policy has to ensure that physically “green” electricity from renewable sources is used for H_2 production by electrolysis.

	lyser and methanation unit with a storage unit for hydrogen has to be optimised, e.g. using storage facilities. The economically equilibrium of further invest in hardware and possibly full utilisation of workload has to be identified.		
Comprehen-sive aspects	General aspects In general, CO_2 reuse has a limited potential and it has to be flanked by other activities as energy efficiency measures in households, public, industry etc. as well as by R&D activities dealing with a more sustainable energy production (including energy storage systems to ensure security of supply and development of market models to ensure competitive prices for the energy supply) Comparative life-cycle oriented analyses are needed on the use of CO_2 and carbon rich waste which is transformed to platform chemicals (such as methanol, methane and syngas) using renewable energy such as wind power in order to determine which process chains and products are associated with highest resource efficiency and lowest GHG emissions. The analysis should comprise cross-sectoral comparisons in order to determine whether the use of renewable energy capacities and CO_2 sources should be directed towards chemical production or transport (if e.g. renewable SNG is used for either purpose) For the introduction of policies and measures for CO2 mitigation, uncertainties about utilization potential and/or limited CO2 sources should be kept in mind. Ecological soundness CO_2 reuse (including PtF / PtG) only makes sense, if renewable electricity structures (generation and transport) and electrolysis infrastructure are build up at the same time in large scale. If an H_2 and CO_2-reuse infrastructure is constructed, potential lock-in effects might be created in times when renewable electricity is not available. Therefore, risks of increased fossil power use has to be taken in mind. This issue must be politically addressed. As the capacities for renewable energy supply are limited, its use for CO_2 transformation to hydrocarbons should be directed towards those process chains and final products which provide the highest resource efficiency and least GHG emissions. Political funding should also orientate on these aspects. Systems analytical perspective Due to the complex systems structure and relationships linked with the value chains for the utilisation of CO_2, a systems analytical perspective for process development and assessment is recommended for the a) assessment of *individual value chains* b) compatibility of value chains with the *industrial system and the energy system in general*. A holistic approach could integrate an LCA with a set of specific impact categories into the technology development process in an early stage of technology development. In a long-term technology foresight process possible chances and hurdles as well as drivers and barriers for the future implementation of the considered value chains can be recognised. Perception Research activities on acceptance and communication regarding CO_2 reuse technologies are needed. Communication on CO_2 reuse technologies must differentiate between the specific variability of this technology and should include all potential risks and benefits linked with CO_2 reuse technologies. The way of representing must be “translated” to each target group: transparent (source), well-balanced (pros and cons), comprehensible (for each group), country-specific (according to		

	different circumstances) and accessible for everybody. It is recommended to involve as early as possible various stakeholders from NGOs, science, industry, economy and policy.

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Annex

Table A 1: Analysed plants (> 0.4 Mt CO_2 per year) and their flue gas emissions

Company	Postcode	Sector	Mt CO2*	kg CO	kg SOx/SO2	kg NOx/NO2	kg NH3
DK Recycling und Roheisen GmbH Duisburg	47053	iron+steel industry	0,7	526.000	857.000	150.000	
	47259	iron+steel industry	4,8	209.000.000	6.450.000	2.790.000	
ThyssenKrupp Steel Europe AG Beeckerwerth	47166	iron+steel industry	0,9	6.530.000	272.000	650.000	
ThyssenKrupp Steel Europe AG Bruckhausen	47166	iron+steel industry	0,5	3.550.000	332.000	456.000	
ThyssenKrupp Steel Europe AG Hamborn	47166	iron+steel industry	2,6	2.090.000	476.000	391.000	
ThyssenKrupp Steel Europe AG Schwelgern	47166	iron+steel industry	5,3	168.000.000	11.500.000	5.760.000	
		Subtotal Iron & Steel Industry	14,8				
Ruhr Oel GmbH Werk Scholven	45896	refinery	3,7		2.710.000	1.440.000	58.900
Ruhr Oel GmbH Werk Horst	45899	refinery	1,0		1.750.000	769.000	
	50997	refinery	1,4		223.000	1.210.000	
	50389	refinery	2,0		1.400.000	1.120.000	
		Subtotal Refineries	8,1				
Pruna Betreiber GmbH Duisburg	47166	cokery	1,9	602.000	634.000	1.480.000	
Arcelor Mittal Bremen GmbH Kokerei Prosper Bottrop	46236	cokery	0,4	854.000	692.000	760.000	
		Subtotal Coke ovens	2,3				
LyondellBasell GmbH Wesseling	50389	chemical industry	2,2			873.000	11.400
	50769	chemical industry	3,0		415.000	1.700.000	
Sachtleben Chemie GmbH Duisburg	47198	chemical industry	0,4		625.000	236.000	
	40589	chemical industry	0,4			325.000	
Solvay Chemicals GmbH Rheinberg	47495	chemical industry	0,9	10.500.000	533.000	968.000	176.000
Evonik Degussa GmbH Marl	45772	chemical industry	2,4		1.180.000	2.050.000	
		Subtotal Chemical Industry	9,3				
CEMEX WestZement GMBH Beckum	59269	cement+lime industry	0,7	525.000	359.000	639.000	80.700
Dyckerhoff AG Lengerich	49525	cement+lime industry	1,1	2.290.000		691.000	41.700
HeidelbergZement AG Ennigerloh	59320	cement+lime industry	0,6	4.260.000	378.000	379.000	110.000
HeidelbergZement AG Geseke	59590	cement+lime industry	0,7	2.260.000		695.000	171.000
Portland-Zementwerke Gebr. Seibel GmbH&Co. KG	59597	cement+lime industry	0,4	3.510.000	367.000	378.000	
Portland-Zementwerke Gebr. Seibel GmbH&Co. KG	59597	cement+lime industry	0,4	1.060.000		315.000	26.800
	59597	cement+lime industry	0,5	5.460.000		407.000	61.700
	42489	cement+lime industry	2,0	3.760.000	630.000	1.170.000	
	58710	cement+lime industry	0,8			314.000	
Spenner Zement GmbH&Co KG Erwitte	59597	cement+lime industry	0,7	1.150.000		695.000	12.900
		Subtotal Cement+Lime Industry	7,9				
		Sum Industrial Plants	**42,4**				
AGR mbH Herten	45699	waste to energy plant	0,6			502.000	
AWG mbH Wuppertal	42349	waste to energy plant	0,4			151.000	
GMVA Oberhausen	46049	waste to energy plant	0,7			638.000	
MVA Bielefeld	33609	waste to energy plant	0,4				
RWE MHKW Essen-Karnap	45329	waste to energy plant	0,6			215.000	
		Subtotal Waste to Energy	2,7				
Currenta GmbH&Co OHG Krefeld	47829	CHP power plant (hard coal)	1,1		446.000	526.000	
Currenta GmbH&Co OHG Leverkusen	51368	CHP power plant (hard coal)	1,0		581.000	450.000	
E.On Kraftwerke Datteln (Inbetr. Neubau 2015?)	45711	CHP power plant (hard coal)	15,8		1.100.000	1.050.000	
Evonik AG/RWE Power AG Bergkamen A	59192	CHP power plant (hard coal)	3,2		2.590.000	2.230.000	23.100
	49749	CHP power plant (hard coal)	4,9		1.200.000	3.170.000	
Evonik AG Herne	44653	CHP power plant (hard coal)	2,3		1.330.000	1.510.000	16.900
Evonik AG Duisburg Walsum	47179	CHP power plant (hard coal)	1,9		1.380.000	1.350.000	13.200
SW Duisburg Hochfeld 1	47053	CHP power plant (hard coal)	0,4		169.000	250.000	
	44537	CHP power plant (hard coal)	1,4		952.000	915.000	10.600
	44536	CHP power plant (hard coal)	2,8				
WSW Elberfeld	42117	CHP power plant (hard coal)	0,5		203.000	271.000	
		Subtotal CHP (hard coal)	35,3				
	50735	CHP power plant (natural gas)	0,9			514.000	
	40221	CHP power plant (natural gas)	0,4			303.000	
Rhein Energie AG Merkenich	50769	CHP power plant (natural gas)	0,6		176.000	462.000	
SW Duisburg AG Wanheim	47249	CHP power plant (natural gas)	0,4			161.000	
RWE Power AG Huckingen	47259	CHP power plant (natural gas)	4,2		819.000	386.000	
RWE Power AG / Currenta Dormagen	41539	CHP power plant (natural gas)	1,5			640.000	
		Subtotal CHP (natural gas)	8,0				
		Sum CHP and Waste-to-Energy Power Plants	**46,0**				
		Threshold value PRTR:	**0,1*** **	**500.000**	**150.000**	**100.000**	**10.000**

* Subroundet values

** Comissioning in 2013, thus estimated values

*** Diverging threshold chosen by Wuppertal Institute: 0.4 Mt/yr

Source: Own compilation, based on (PRTR 2012)

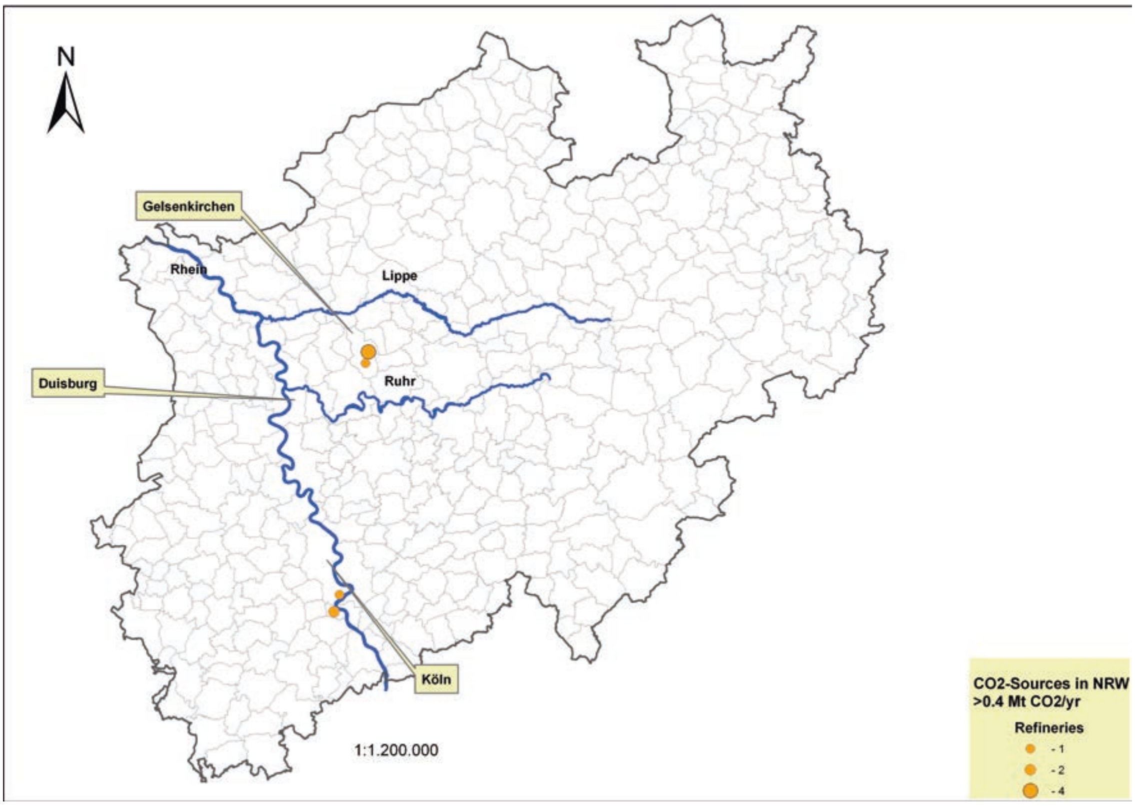

Figure A 1: Refineries in NRW (> 0.4 Mt CO_2 per year)

Source: Own figure

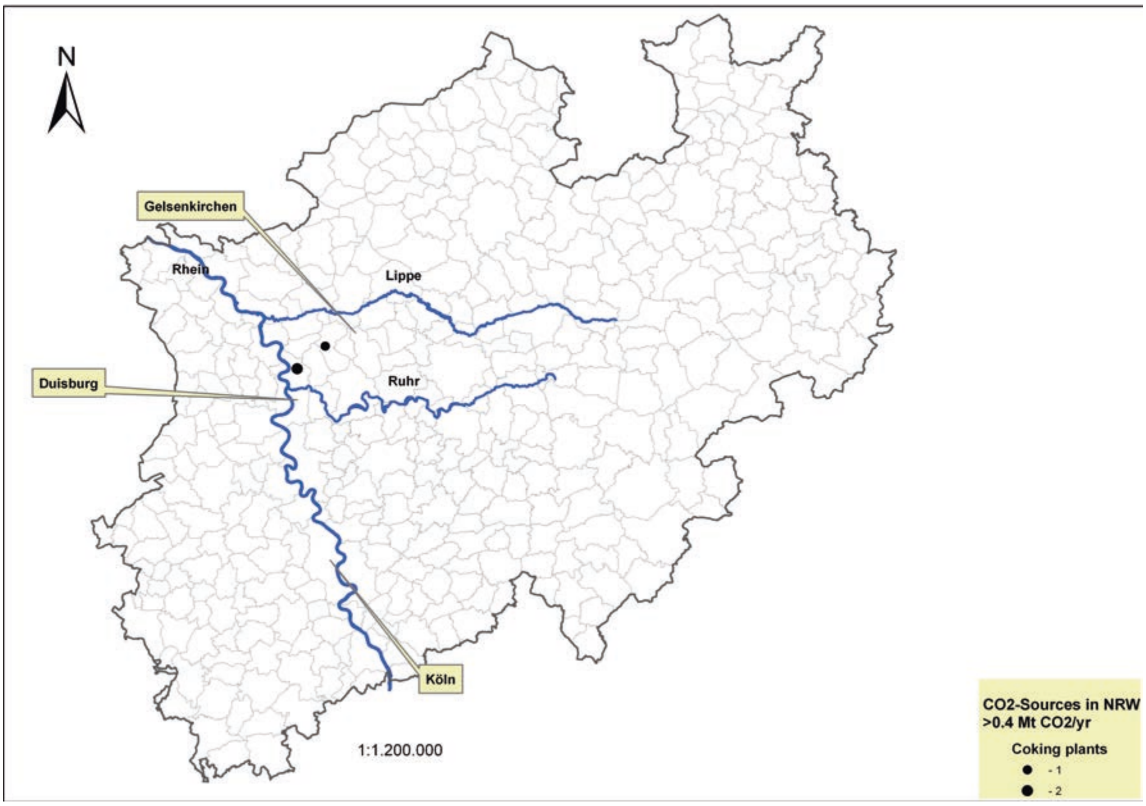

Figure A 2: Coking plants in NRW (> 0.4 Mt CO_2 per year)

Source: Own figure

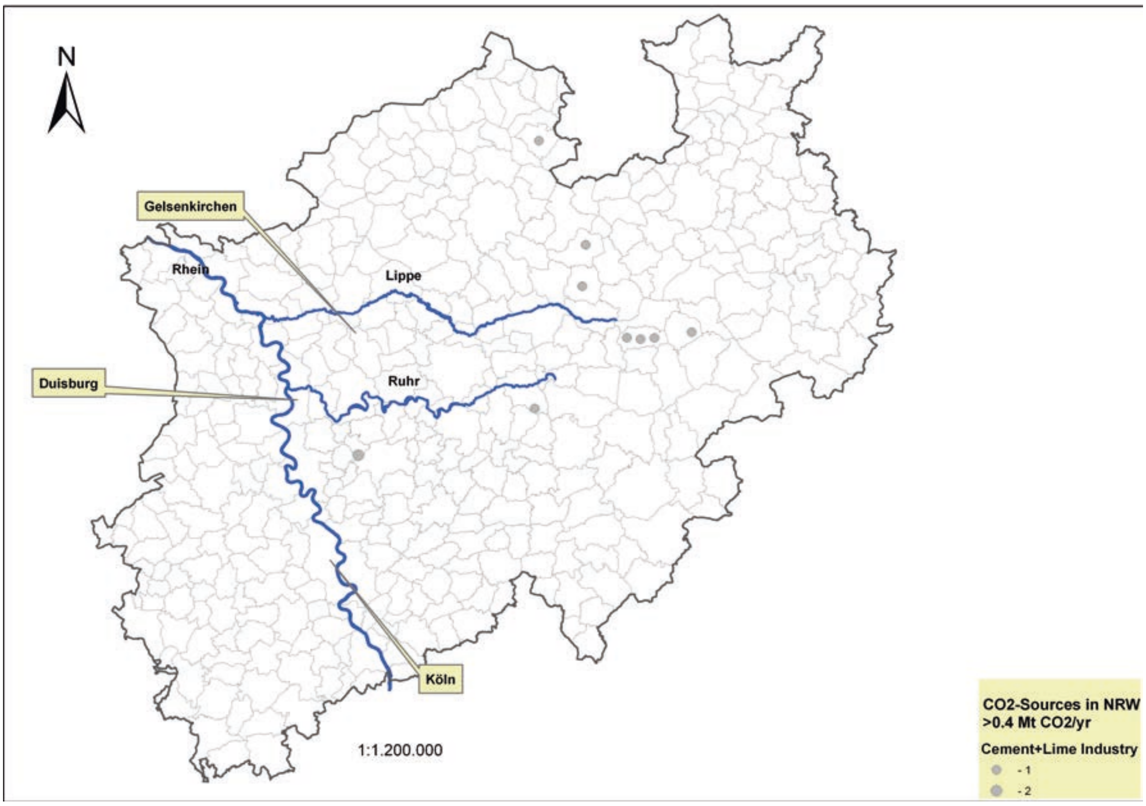

Figure A 3: Cement and lime industry plants in NRW (> 0.4 Mt CO_2 per year)

Source: Own figure

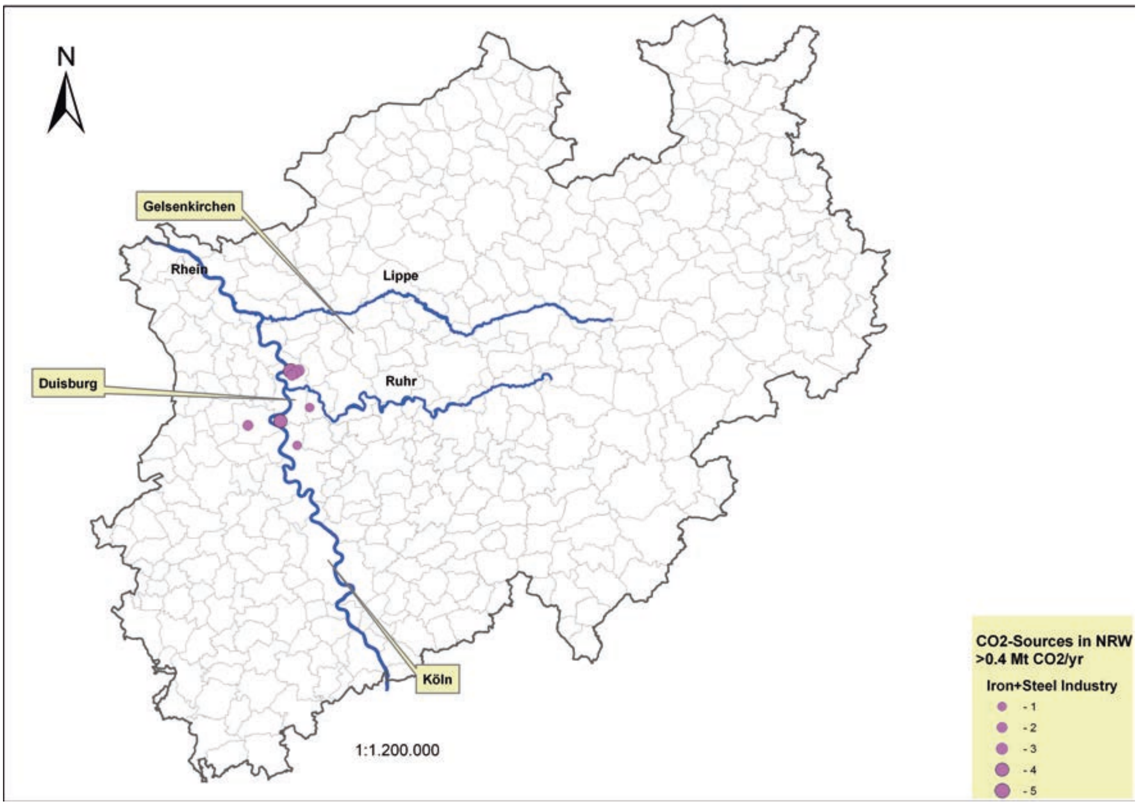

Figure A 4: Iron and steel industry plants in NRW (> 0.4 Mt CO_2 per year)

Source: Own figure

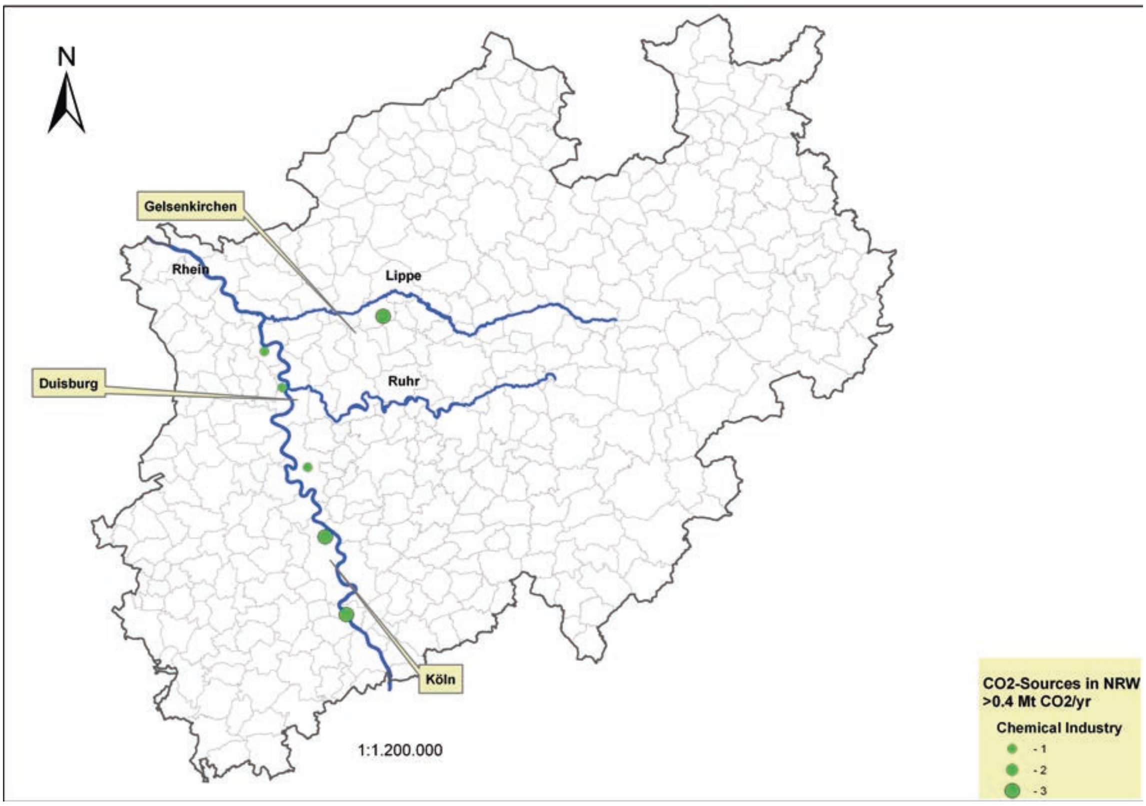

Figure A 5: Chemical industry plants in NRW (> 0.4 Mt CO_2 per year)

Source: Own figure

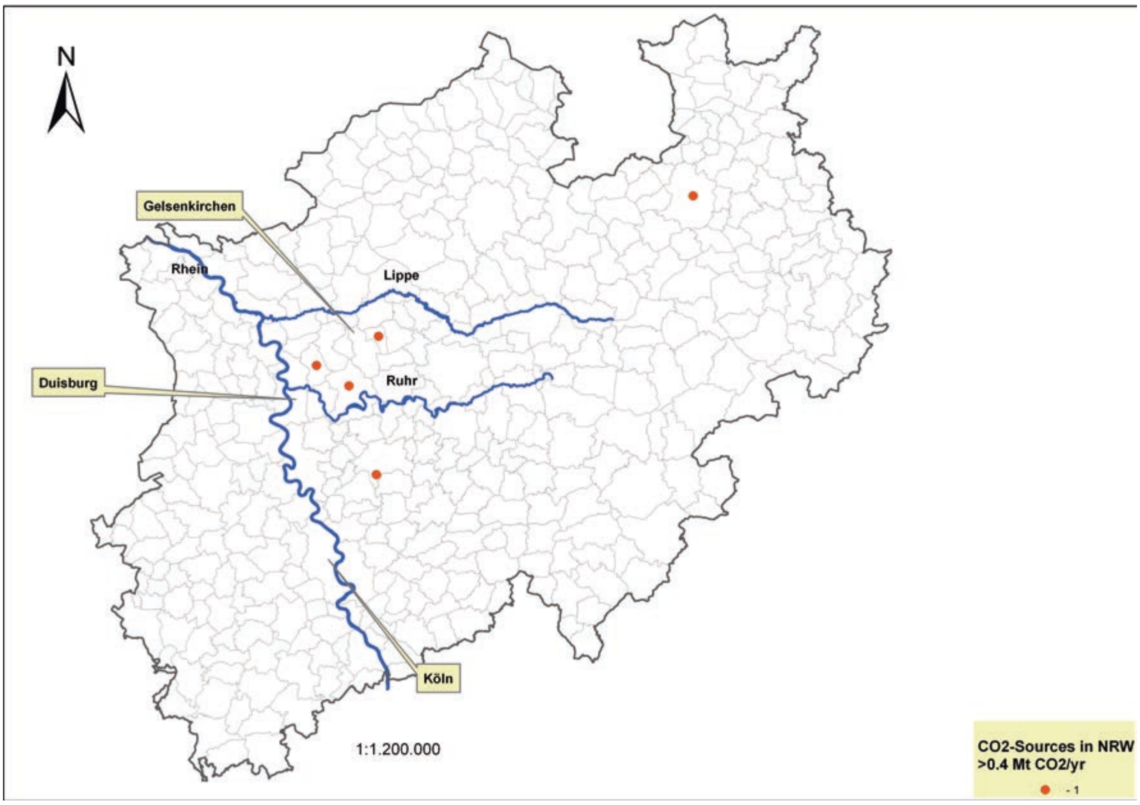

Figure A 6: Waste-to-energy plants in NRW (> 0.4 Mt CO_2 per year)

Source: Own figure

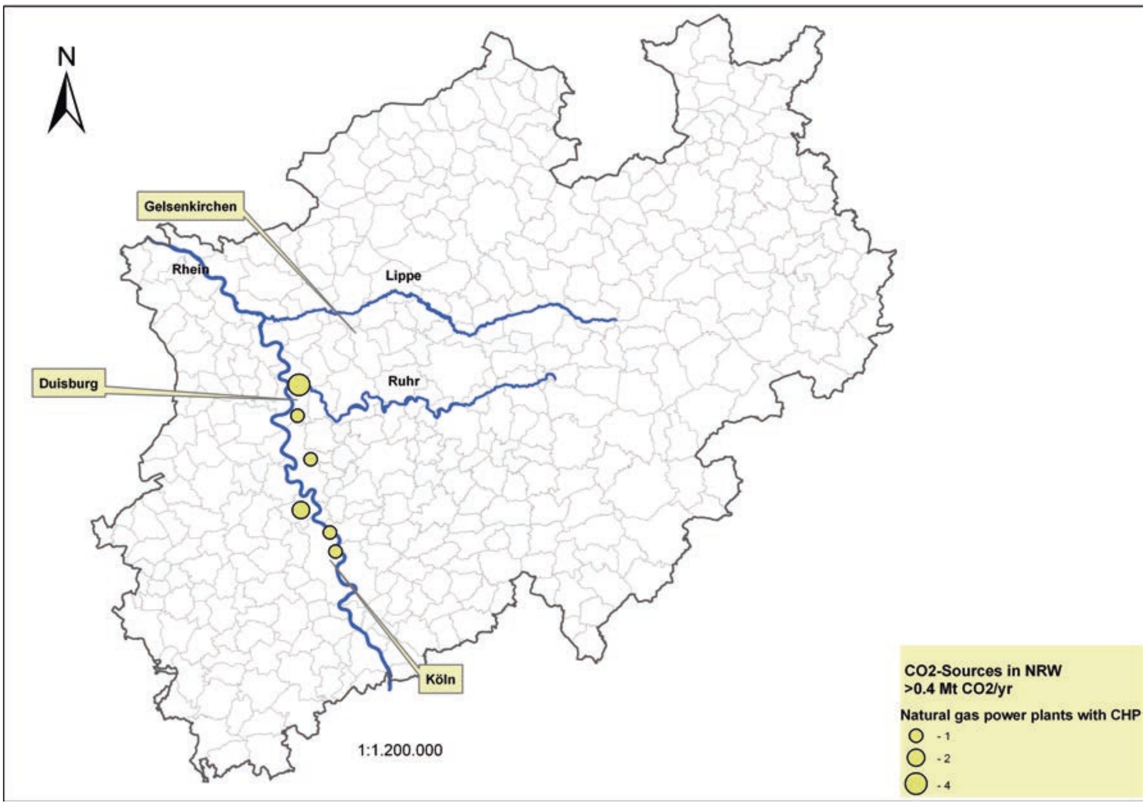

Figure A 7: Natural gas power plants with CHP in NRW (> 0.4 Mt CO_2 per year)

Source: Own figure

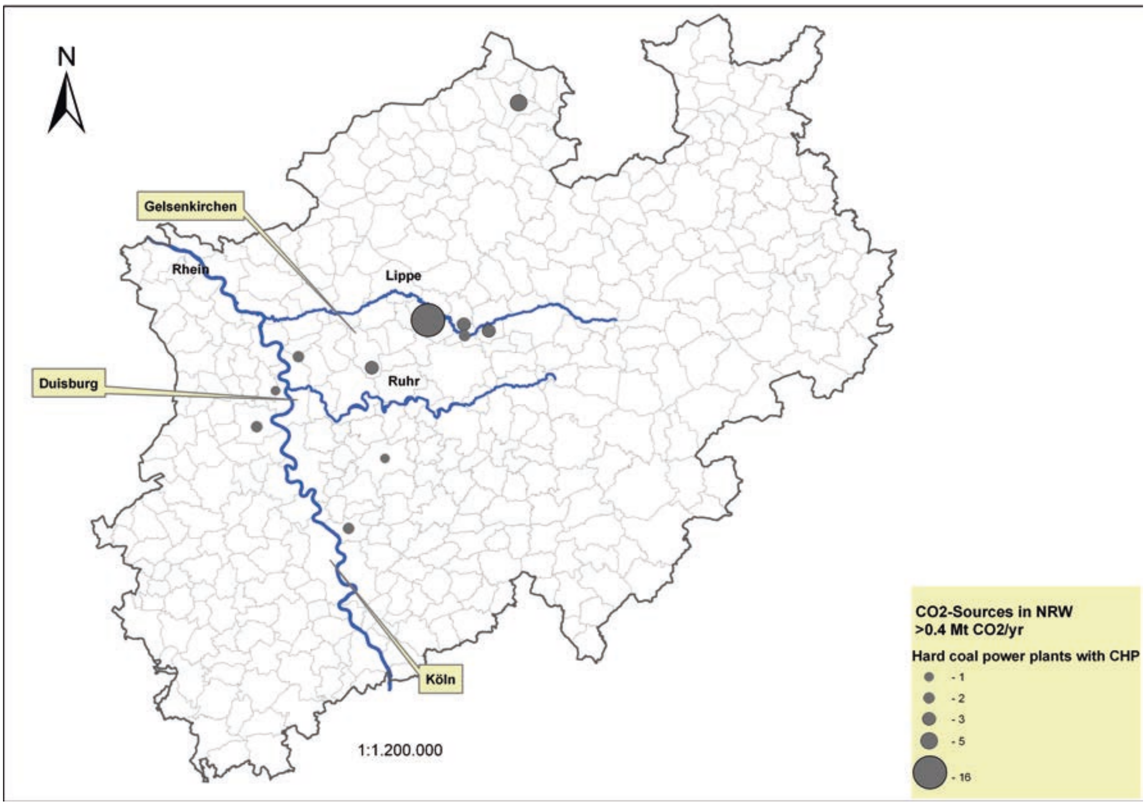

Figure A 8: Hard coal power plants with CHP in NRW (> 0.4 Mt CO_2 per year)

Source: Own figure

Table A 2: List of projects of CO_2 reuse in the chemical industry funded by the German BMBF

Title of project	Institution	Contact
Acrylic Acid from CO_2 and Ethene (ACER)	BASF SE	Dr. Michael Limbach michael.limbach@basf.com
CO_2 as a Polymer Building Block	BASF SE	Dr. Uwe Seemann uwe.seemann@basf.com
Integrated Dimethyl ether Synthesis Based on Methane and CO_2 (DMEexCO_2)	BASF SE	Dr. Ekkehard Schwab ekkehard.schwab@basf.com
Solid and liquid Products from Gas	BASF SE	Dr. Dirk Klingler dirk.klingler@basf.com
Dream Polymers	Bayer MaterialScience AG	Dr. Christoph Gürtler christoph.guertler@bayer.com
Dream Production – Technical utilization of CO_2 as a Chemical synthesis Building Block for Polymers	Bayer MaterialScience AG	Dr. Christoph Gürtler christoph.guertler@bayer.com
Dream reactions - CO_2 utilization	Bayer Technology Services GmbH	Dr. Aurel Wolf aurel.wolf@bayer.com
CO_2-Based Acetone Fermentation (COOBAF)	Evonik Industries AG	Dr. Jörg-Joachim Nitz joerg-joachim.nitz@evonik.com
Energy-efficient Synthesis of Aliphatic Aldehydes from Alkenes and CO_2: Valeraldehyde from Butane and CO_2 (Valery)	Evonik Industries AG	Dr. Daniela Kruse daniela.kruse@evonik.com
New Organocatalysts and Cooperative Catalytic Processes for the Utilization of CO_2 as a Building Block for Chemical Synthesis (OrgCoCat) – Junior Research Group	Leibniz-Institut für Katalyse e. V.	Dr. Thomas Werner thomas.werner@catalysis.de
Combinatorial Electrocatalytic CO_2 Reduction (ECCO_2) – Junior Research Group	Max-Planck-Institut für Eisenforschung GmbH	Dr. Karl J.J. Mayrhofer mayrhofer@mpie.de
Development of Active and Selective Heterogeneous Photocatalysts for the Reduction of CO_2 to C1 Base Chemicals (PhotoCat) – Junior Research Group	Ruhr-Universität Bochum	Dr. Jennifer Strunk jennifer.strunk@techem.rub.de

Source: (BMBF 2014 p. 5)

Table A 3: List of Power-to-Gas demonstration projects in Germany with different technological foci

	Project title	Project start	Status	Fuel	Injection	Metha-nation	Elec-tricity	Storage	Waste heat	H2 as feedstock	Heat
1	Windpark RH2-WKA	2009	Operation	x			x		x		
2	H2-Forschungszentrum Cottbus	2010	Operation				x	x			
3	Wasserstofftankstelle HafenCity	2011	Operation	x							
4	Hybridkraftwerk Prenzlau	2011	Operation	x	x			x	x		
5	Audi e-gas Projekt	2011	Operation	(Methane)		x					
6	H2Herten	2011	Operation	x							
7	CO2rrect	2011	Operation			x					
8	WindGas Falkenhagen	2012	Operation		x						
9	RWE- Demonstrationsanlage	2012	Construction		x						
10	Multi-Energie-Tankstelle H2BER	2012	Operation	x	x		x	x	x		
11	Methanisierung auf dem Eichhof	2012	Operation			x					
12	Sunfire Power-to-Liquids	2012	Construction	x							
13	Thüga- Demonstrationsanlage	2012	Operation		x		x				
14	Power to gas im Eucolino	2012	Construction			x					
15	Verbundprojekt "Power– to- Gas"	2012	Operation			x					
16	WindGas Hamburg	2013	Construction		x						
17	HYPOS	2013	Planning		x	x		x		x	
18	BioPower2Gas / Viessmann Anlage Allendorf	2013	Construction		(Methane)	x					(Methane)
19	Energiepark Mainz	2013	Construction	x	x		x	x		x	x
20	Mikrobielle Methanisierung	2013	Operation			x	(Methane)				(Methane)

Source: Own compilation based on "Strategieplattform Power-to-Gas" (Dena)[37]

Table A 4: List of projects of CO_2 reuse for chemical energy storage funded by the German BMBF

Title of project	Institution	Contact
Solar-thermal synthesis of Chemical Products from H_2O and CO_2 (Solar STEP)	BASF SE	Dr. Michael Göbel michael.goebel@basf.com
Utilization of CO_2 as a Carbon Building Block Mainly using renewable energy (CO2RRECT)	Bayer Technology Services	Dr. Oliver F.-K. Schlüter oliver-fk.schlueter@bayer.com
Storage of electrical energy from renewable resources in the Gas Grid (SEE)	DVGW-Forschungsstelle	Dipl.-Ing. Dominic Buchholz buchholz@dvgw-ebi.de
New catalysts and technologies for solar-chemical hydrogen production (HyCats)	H.C. Starck GmbH	Dr. Sven Albrecht sven.albrecht@hcstarck.com
Synthesis of Fuels using CO_2 and Water using renewable energy (SunFire)	Sunfire GmbH	Christian von Olshausen christian.vonolshausen@sunfire.de
Integrated Carbon Capture, Conversion and Cycling (iC4)	Technische Universität München	Prof. Dr. Dr.h.c Bernhard Rieger rieger@tum.de

Source: (BMBF 2014 p. 11)

37 www.powertogas.info/de/power-to-gas/interaktive-projektkarte.html, accessed at 19. December 2014

Figure A 9: Power-to-Gas and hydrogen projects in Germany
Source: (DVGW o.J.)

Table A 5: Global Processes of CO_2 utilization

Production sector (NACE)	Utilization process	Quantity	Source
Total use of CO_2		80 Mt/a	Global CCS Institute (2011)
Extraction of crude petroleum and natural gas (06)	Enhanced Oil Recovery (EOR)	54 Mt/a	Global CCS Institute (2011) qtd. in Muradov (2014)
		50 Mt/a (USA & Canada)	Global CCS Institute (2011)
	Oil and gas industry (other than EOR)	1.12 Mt/a	Global CCS Institute (2011) qtd. in Muradov (2014)
Manufacture of food products (10)	Food processing, preservation and packaging	9.68 Mt/a	Global CCS Institute (2011) qtd. in Muradov (2014)
Manufacture of beverages (11)	Beverage carbonation	5.36 Mt/a	Global CCS Institute (2011) qtd. in Muradov (2014)
Manufacture of chemicals and chemical products (20)	Cyclic carbonates	0.04 Mt/a	Li et al. (2006)
	Dimethyl carbonate	< 0.1 Mt/a	Zevenhoven et al. (2006)
	Inorganic compounds	18.5 Mt/a	Zevenhoven et al. (2006)
	Inorganic carbonates	a few ten's kt/a	(Aresta and Tommasi 1997)
	Inorganic carbonates and pigments	30 Mt/a	Aresta & Dibenedetto (2007)
	Methanol synthesis (via hydrogen-rich syngas)	6 Mt/a	Aresta & Dibenedetto (2007)
		2 Mt/a	Ausfelder & Bazzanella (2008)
		2 Mt/a	Li et al. (2006)
		Variable amounts up to several Mt/a	(Aresta and Tommasi 1997)
	Precipitated $CaCO_3$	2.48 Mt/a	Global CCS Institute (2011) qtd. in Muradov (2014)
	Synthesis of cyclic carbonates	0.040 Mt/a	Ausfelder & Bazzanella (2008)
	Synthesis of polycarbonates	0.4 Mt/a	Zevenhoven et al. (2006)
		only a few kt/a	(Aresta and Tommasi 1997)
	Salicylic acid synthesis (via Sodium phenylate)	0.025 Mt/a	Ausfelder & Bazzanella (2008)
		0.02 Mt/a	Aresta & Dibenedetto (2007)

Production sector (NACE)	Utilization process	Quantity	Source
		ca. 0.02 Mt/a	(Aresta and Tommasi 1997)
	Technological fluids	18	Aresta & Dibenedetto (2007)
	Urea synthesis (captive)	113 Mt/a	Global CCS Institute (2011) qtd. in Muradov (2014)
		80 Mt/a	Ausfelder & Bazzanella (2008)
		70 Mt/a	Aresta & Dibenedetto (2007)
		30 Mt/a	(Aresta and Tommasi 1997)
Other	Other liquid CO_2 Applications	6.48 Mt/a	Global CCS Institute (2011) qtd. in Muradov (2014)
	Others	0.88 Mt/a	Global CCS Institute (2011) qtd. in Muradov (2014)

Table A 6: Global Processes of H_2 utilization

Production sector (NACE)	Utilization process	Quantity	Source
Total		50 Mt/a	The Essential Chemical Industry (2013)
		45 Mt/a	(International Partnership for Hydrogen and Fuel Cells in the Economy 2011)
		41.09 Mt/a	Suresh et al. (2004) qtd. in Argonne National Laboratory (2003)
		7.8 Mt/a (Europe)	Le Duigou et al. (2011)
Extraction of crude petroleum and natural gas (06)	Refinery processes	11.26 Mt/a	Suresh et al. (2004) qtd. in Argonne National Laboratory (2003)
		10 Mt/a	The Essential Chemical Industry (2013)
Manufacture of chemicals and chemical products (20)	Ammonia synthesis	26.5 Mt/a	The Essential Chemical Industry (2013)
		23.63 Mt/a	Suresh et al. (2004) qtd. in Argonne National Laboratory (2003)
	Methanol synthesis	3.99 Mt/a	Suresh et al. (2004) qtd. in Argonne National Laboratory (2003)
		3.5 Mt/a	The Essential Chemical Industry (2013)
Other	Others	10 Mt/a	The Essential Chemical Industry (2013)
		0.47 Mt/a	Suresh et al. (2004) qtd. in Argonne National Laboratory (2003)